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Recommendations of the International Commission on Radiological Protection

(*Revised December* 1, 1954)

PUBLISHED BY THE BRITISH INSTITUTE OF RADIOLOGY

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FOREWORD

By J. A. C. FLEMING, M.B., F.R.C.S.E., F.F.R., D.R.
President of the British Institute of Radiology

This Supplement appears as the result of an invitation to Council of the British Institute of Radiology from the International Commission on Radiological Protection (I.C.R.P.) to publish the English version of the latest Report of the Commission.

It marks the latest link in a chain of events extending back at least to 1921, when a few members of the Institute were meeting informally to consider what practical steps could be taken to protect radiologists from the injurious effects of the penetrating radiations from radium and from X-ray machines. The group engaged in those discussions became the original British X-ray and Radium Protection Committee, officially recognised as such in the Spring of 1921, which was about six months after the formation of the Röntgen Ray Protection Committee of the U.S.A. The British recommendations on protection, were, however, the first in the world to be published. Other countries soon followed by setting up their own Committees charged with the duty of drawing up safety regulations for all persons whose work exposed them to penetrating rays.

Action on an international scale was taken at the 2nd International Congress of Radiology at Stockholm in 1928, when recommendations, largely on the British pattern, were drawn up by the I.C.R.P. and subsequently issued as the first of a series of Reports, of which the present volume is the latest representative. Some idea of the growth and complexity of the problem during these 15 years can be gained from a comparison of the first (British Committee) 1500-word report with the size of this latest I.C.R.P. Report comprising some 90 pages of print.

The rapidly increasing range of radiation sources which became available with the development of artificial radioactivity made it advisable to extend and reorganise the committees concerned with protection problems, both on the national and international levels. In the reorganisation in Great Britain the British X-ray and Radium Protection Committee handed over their responsibilities to other bodies working under the Medical Research Council and the Ministry of Health, which maintains the closest collaboration with International Committees, from one of which (I.C.R.P.) the following report issues. It represents an interim statement in the light of present knowledge which will serve those concerned with the problems of protection until the results of further experiment and observation have been accumulated.

RADIOLOGICAL PROTECTION SERVICE

Information concerning all aspects of radiological protection
to be obtained from the
Radiological Protection Service,
(Ministry of Health and Medical Research Council)
at Downs Nursery Hospital,
Cotswold Road,
Sutton, Surrey.

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A. INTRODUCTION

I. RULES GOVERNING THE SELECTION AND WORK OF THE INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION

The International Commission on Radiological Protection (I.C.R.P.) functions under the auspices of the International Congress of Radiology. The Commission was first set up in 1928 to make recommendations on radiation safety standards. The following rules, amended in 1953 by the International Executive Committee (I.E.C.) of the Congress, govern the selection and work of the I.C.R.P.

1. (*a*) The International Commission on Radiological Protection (I.C.R.P.) shall be composed of a Chairman and not more than 12 members. The selection of members shall be made by the International Executive Committee (I.E.C.) from a list of nominations submitted by the national delegations and by the International Commission on Radiological Protection itself. Members of the I.C.R.P. shall be chosen on the basis of their recognised activity in the fields of radiology, radiation protection, physics, biology, genetics, biochemistry, and biophysics, without regard to nationality.

   (*b*) The members of the I.C.R.P. shall be selected during one International Congress to serve through the succeeding Congress. Not less than two, but not more than four, members of the I.C.R.P. shall be changed at each Congress. In the intervening period a vacancy caused by conditions beyond the control of the I.E.C. shall be filled on the recommendation of the I.C.R.P.

   (*c*) In the event of a member of the I.C.R.P. being unable to attend the I.C.R.P. meetings, a substitute may be selected by the I.C.R.P. as a temporary replacement. Such a substitute member shall not have voting privileges at the meetings unless specifically authorised by the I.E.C.

   (*d*) The I.C.R.P. shall be permitted to invite individuals to attend its meetings to give special technical advice. Such persons shall not have voting privileges, but may ask permission to have their opinion recorded in the minutes.

2. The continuance of the records of the I.C.R.P. shall be in the hands of a Secretary of the I.C.R.P. elected by the I.C.R.P. from among its regular members and subject to the approval of the I.E.C.

3. The I.C.R.P. shall familiarise itself with progress in the whole field of radiation protection. The Secretary shall be responsible for the preparation of a programme to be submitted to the Commission for discussion at its meetings. Preliminary reports shall be prepared and circularised to all members of the I.C.R.P. and other specially qualified individuals at least six months before the meeting of the Congress.

4. The Chairman shall be elected by the I.C.R.P. during one Congress to serve through the succeeding Congress. The choice shall not be limited to the country in which it is proposed to hold the succeeding Congress.

5. Decisions of the I.C.R.P. shall be decided by a majority vote, with the Chairman casting the deciding vote in case of a tie. A minority opinion may be appended to the minutes of a meeting if so desired by any member and upon his submission of same in writing to the Secretary.

II. POLICY OF THE COMMISSION

The policy adopted by the I.C.R.P. in preparing its recommendations on radiation safety standards is to deal with the basic principles of radiation protection, and to leave to the various national protection committees the right and responsibility of introducing the detailed technical regulations, recommendations, or codes of practice best suited to the needs of their individual countries.

The Commission's recommendations have been kept continually under review in order to cover the increasing number and scope of potential radiation hazards, and to amend the safety factors in the light of new knowledge concerning the effects of ionizing radiations.

III. ORGANISATION OF INTERNATIONAL SUB-COMMITTEES

The preparation of the last Recommendations of I.C.R.P. (1950) followed a period of rapid development in the field of nuclear physics and of high-energy radiation. The Commission then realised the need to establish a number of Sub-Committees to carry out, between Congresses, detailed studies in the various specialised fields of radiological protection. Six Sub-Committees were suggested, namely:

i. Permissible dose for external radiation.
ii. Permissible dose for internal radiation.
iii. Protection against X rays generated at potentials up to two million volts.
iv. Protection against X rays above two million volts, and against β rays and γ rays.
v. Protection against heavy particles, including neutrons and protons.
vi. Disposal of radioactive wastes; handling of radioactive isotopes.

With the exception of Sub-Committee VI, the Sub-Committees appointed by the Commission prepared reports regarding radiation protection in their respective fields. They met in Copenhagen during the week prior to the Seventh International Congress of Radiology (July 1953), to discuss these reports and, if possible, present them in final form to the main Commission for submission to the International Congress of Radiology. This was, however, not possible for, whilst agreement was reached about basic principles, the preliminary reports had, for a variety of reasons, to be appreciably modified subsequent to the Congress. For example, (*a*) the decisions of some Sub-Committees affected the reports of others, and (*b*) the calculations which had been made to assess the maximum permissible levels for a large number of radioactive isotopes had to be reviewed because of the decision of the International Commission on Radiological Units (I.C.R.U.) to introduce a new unit of dose of ionizing radiation, and because Sub-Committee II realised, during its Copenhagen meetings, that the gastrointestinal tract, which had hitherto been ignored, might be the critical organ most affected by some isotopes. The Sub-Committees thus affected have, therefore, subsequent to the Copenhagen Congress, expended considerable effort in preparing the revised reports which are now presented.

As no members of Sub-Committee V could attend the Copenhagen meetings, it was decided to unite this Sub-Committee with Sub-Committee IV.

Since the original Sub-Committee VI had not been able to prepare a report, nor were any of the members able to visit Copenhagen, it was found necessary to set up a new Sub-Committee to deal with the handling and disposal of radioactive isotopes. When the report on these aspects is available, it will be published as an addendum to the present I.C.R.P. report.

It will be appreciated that the division of the work of preparing radiological protection recommendations amongst the several Sub-Committees is quite an arbitrary one and that there is, in fact, a considerable overlapping of interests. In the circumstances the repetition of certain statements in the various Sub-Committee reports is unavoidable.

IV. PRESENT COMPOSITION OF THE I.C.R.P. AND THE INTERNATIONAL SUB-COMMITTEES

It was not known, when the proposal was made to establish Sub-Committees to deal with the various aspects of radiation protection, whether such an arrangement would prove to be satisfactory. It has been decided to continue this scheme for a further trial period; the only changes which have been made are that:

(*a*) Sub-Committee III will deal with protection against X rays up to three million volts,

(*b*) Sub-Committee IV will deal with protection at higher energies and

(*c*) Sub-Committees IV and V are re-constituted as one Sub-Committee to deal with the closely allied sections of high-energy radiation and of heavy particles.

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W. Binks, Secretary (Great Britain)
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G. Failla (U.S.A.)
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Sub-Committee V. (Handling and disposal of radioactive isotopes)

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V. DEFINITIONS OF SCIENTIFIC TERMS

Some of the terms used in this composite report apply solely to the field covered by one Sub-Committee. Accordingly, these terms are defined in the report of the Sub-Committee concerned. Terms of common usage in several fields are defined below.

Absorbed dose of any ionizing radiation: amount of energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest. It shall be expressed in rads. (See Recommendations of I.C.R.U., Copenhagen, 1953.)

Air dose (*free-air dose*): a dose of radiation measured in air at the point of interest, in the absence of patient (or phantom) or other object, thus excluding secondary radiation, apart from that arising from the air or associated with the source.

Applicator: an attachment to an X-ray therapy tube head or telecurie therapy unit designed so that it defines the cross-section of the radiation beam at a given distance from the X-ray target. It may also help to prescribe the distance between the X-ray target and the skin of the patient. It is sometimes called an *X-ray therapy applicator, telecurie therapy nozzle,* or *treatment cone.*

Atomic number (Z)*:* number of orbital electrons in a neutral atom, or the electric charge on the nucleus of the atom, or the number of protons in the nucleus of an atom. (The nucleus of an atom is considered as consisting of protons and neutrons. The number of protons governs the positive charge on the nucleus and hence the number of orbital electrons needed to produce a neutral atom.)

Attenuation: decrease in dose-rate of radiation in passing through a material.

(1) *Narrow beam* (*good geometry*) *attenuation:* attenuation obtained under conditions designed effectively to prevent the inclusion of scattered radiation in the transmitted beam.

(2) *Broad beam* (*bad geometry*) *attenuation:* attenuation obtained under such conditions that the maximum amount of scattered radiation is included in the transmitted beam.

Barium plaster (*or concrete*)*:* plaster or concrete containing a high proportion of barytes (barium sulphate). Used as a protective building material.

Collimation: the limiting of a beam of radiation to the required dimensions.

Cone: see "Applicator".

Constant potential (*or voltage*)*:* in radiological practice this term is applied to a uni-directional potential (or voltage) which has only small, or no, periodic variations. The periodic component is called the *ripple potential* (or *ripple voltage*).

Cosmic rays: ionizing rays entering the earth's atmosphere from unidentified extra-terrestrial space and resulting in the presence of photons, electrons, neutrons, protons, mesons, etc., by collisions with atoms in the atmosphere and by radioactive decay.

Critical organ: see reports of Sub-Committees I and II.

Curie: a unit of radioactivity defined as the quantity of any radioactive nuclide (see p. 7) in which the number of disintegrations per second is $3{\cdot}700 \times 10^{10}$. Denoted by "c".

Microcurie (μc): 1/1,000,000 curie.

Millicurie (mc): 1/1000 curie.

Disintegration: process of spontaneous breakdown of a nucleus of an atom resulting in the emission of a particle and/or a photon. The rate of disintegration of a quantity of any radioactive nuclide is a function of the number of atoms present and a disintegration constant characteristic of the nuclide concerned.

Dose: a quantity of radiation as defined in the definition of the unit "röntgen".

Dose-rate: radiation dose received per unit time.

Dosemeter: instrument that measures radiation dose.

Electron volt (*eV*)*:* unit of energy. The change in kinetic energy of an electron when it is accelerated through a potential difference of 1 volt. One eV is equivalent to $1{\cdot}602 \times 10^{-12}$ erg.

Kilo-electron-volt (*keV*)*:* 1000 eV.

Mega-electron-volt or *million electron volt* (*MeV*)*:* 1,000,000 eV.

Energy spectrum: the orderly separation of the components of a beam of radiation according, for example, to their wavelengths, frequencies or quantum energies.

Film-badge: a pack of photographic film and appropriate filters used for the detection of radiation exposure.

Fluorescence: phenomenon involving the absorption of radiant energy by a substance and its re-emission, during the period of radiation excitation, as visible or near-visible radiation.

Fluoroscope: equipment involving a screen of material which fluoresces when irradiated with X rays. It is used in X-ray diagnosis by passing the X-ray beam through a patient or object and allowing it to fall on the screen, thus producing a visible image of the internal structure of the object.

Flux: a rate of flow of radiation across unit area normal to the direction of flow. For example, a neutron flux is the number of neutrons that cross 1 cm^2 per second. (See "Intensity".)

Geiger-Müller counter: a form of ionization chamber equipped with suitable electrodes and operated at a voltage and gas pressure that will permit the multiplication of ionization by collision and in which the total ionization per event to be detected is independent of the amount of ionization produced by the initiating particle or quantum.

Half-life: time taken for the amount of a radioactive nuclide to decrease to half its initial value.

Half-value layer (H.V.L.): the thickness of a specified absorbing material which, when introduced into the path of an X-ray beam, reduces the dose-rate to one half its original value.

Integral absorbed dose: the integration of the energy absorbed throughout a given region of interest. The unit is the gramme-rad. 1 gramme-rad = 100 ergs. (See I.C.R.U.)

Intensity of radiation at a point: energy flowing per unit time through unit area perpendicular to the beam at the point in question. Expressed in ergs per square centimetre per second, or watts per square centimetre. (See I.C.R.U.)

Ionization chamber: a gas-filled enclosure, having electrodes between which an electric field is applied to separate the positively and negatively charged ions formed by the passage of radiation through the gas. It is used to measure or to detect radiation by means of the ionization current produced therein.

Ionizing radiation: electromagnetic radiation (X-ray or γ-ray photons or quanta), or corpuscular radiation (α particles, β particles, electrons, positrons, protons, neutrons and heavy particles) capable of producing ions.

X-rays: electromagnetic ionizing radiation which originates from the field outside the nucleus of the atom, and resulting from loss of energy of charged particles, *e.g.* electrons. Of shorter wavelength than ultraviolet radiation.

γ rays: electromagnetic ionizing radiation which originates within the nucleus of the atom. (Often the terms "X rays" and "γ rays" are used indiscriminately in radiology. Scientifically, there is no distinction between X-ray photons and γ-ray photons of the same energy.)

α particle (α ray): corpuscle consisting of the nucleus of a helium atom and emitted by radioactive atomic nuclei. Usually travelling at high speed.

electron: sub-atomic particle having a rest mass of $9{\cdot}107 \times 10^{-28}$ g and a charge of negative electricity of $4{\cdot}802 \times 10^{-10}$ e.s.u.

positron: sub-atomic particle having a rest mass of $9{\cdot}107 \times 10^{-28}$ g and a charge of positive electricity of $4{\cdot}802 \times 10^{-10}$ e.s.u.

β particle (β ray): an electron (or positron) originating from nuclear processes.

proton: a nuclear particle of unit mass number having a charge equal and opposite to that of an electron. The nucleus of the hydrogen atom (not of the isotopes deuterium and tritium) is a proton.

neutron: radioactive corpuscle which has no electric charge and has a mass slightly greater than that of the proton. It decays with a half-life of 10 to 30 minutes to a proton and an electron.

The type of interaction which occurs between neutrons and atoms depends upon the kinetic energy of the former. If the kinetic energy of the neutrons lies between about 20 keV and 10 MeV (so-called "fast neutrons") or between 10 MeV and 500 MeV (so-called "high energy neutrons"), they can set in motion the nuclei of atoms with which they collide with sufficient velocity to ionize matter. "Slow neutrons", which are usually classed as having energies up to 0·1 eV, and include "thermal neutrons" which have energies (about 0·025 eV) associated with room temperatures, enter into nuclear reactions with atoms they meet, resulting in the emission of ionizing radiations. Between slow and fast neutrons is a group known as "epithermal neutrons" (or "intermediate neutrons").

Isotopes: nuclides having the same atomic number but different mass numbers.

Kilovolt (kV): 1000 volts.

Lead equivalent: the thickness of lead, which, under specified conditions of irradiation, affords the same protection as the material under consideration. The lead equivalent of a substance, such as lead-glass or lead-rubber, which attenuates the radiation essentially by its lead content, is largely independent of the quality of the radiation. The lead equivalent of all other protective materials and also building materials for protective walls (concrete, brick, etc.) and barium protective glass show a dependence on the quality of the radiation. (See report of Sub-Committee III.)

Lead-rubber: rubber containing a high proportion of lead compounds. It is used as a flexible protective material.

Lead-rubber apron (protective apron): a protective shield of lead-rubber. It may be a flap suspended from the fluorescent screen of an X-ray couch or stand, or a garment to be worn by the operator. In the latter case it may be called a "body apron".

Lead-rubber gloves (protective gloves): gloves incorporating lead-rubber as a protective material.

Lead-glass (protective glass): glass containing a high proportion of lead compounds, which absorbs radiation passing through it. Used as a transparent protective material.

Linear energy transfer of an ionizing particle: energy dissipated per unit distance along the path of an ionizing particle.

Local dose-rate: the measured dose-rate in occupied space, with a patient, phantom or other object present in the useful beam.

mA: 1/1000 ampere.

Mass number: total number of protons and neutrons in an atom.

Megavolt or *million volt (MV):* 1,000,000 volts.

Nuclide: a species of atom having a specific mass number, atomic number and energy state.

Occupied (or used) space: a space which may be occupied by personnel and where a radiation hazard may exist.

Permissible dose: dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime. (See report of Sub-Committee I, Section I.1.)

Permissible weekly dose: dose of ionizing radiation accumulated in one week of such magnitude that, in the light of present knowledge, exposure at this weekly rate for an indefinite period of time is not expected to cause appreciable bodily injury to a person at any time during his lifetime. (See report of Sub-Committee I, Section I.2.)

Personnel dose (or personnel dose-rate): the dose (or dose-rate) received by personnel in the course of their work.

Personnel monitoring: continuous or periodic measurement of the personnel dose (or dose-rate). It is complementary to site monitoring (q.v.).

Photon: corpuscular (quantum) manifestation of electromagnetic radiation.

Proportional counter: a form of ionization chamber equipped with suitable electrodes between which an electric field is applied which is high enough to produce ionization by collision and so adjusted that the total ionization per count is substantially proportional to the ionization produced in the gas by particles or quanta of radiation entering the counter.

Protection: provisions designed to reduce exposure of personnel to ionizing radiation.

Protective barrier: material used for absorbing ionizing radiation for protection purposes.

Pulsating potential (or voltage): a potential (or voltage) which undergoes large periodic variations in magnitude at a frequency related to that of the mains supply.

Qualified expert (or health physicist): a person having the knowledge and training needed to measure ionizing radiations and to advise regarding radiation protection. The qualification should be of the type specified by a National Committee.

Quantum: the smallest quantity of energy constituting a photon of electromagnetic radiation which can be associated with a given phenomenon. (Electromagnetic radiation sometimes appears to consist of waves and at other times of particles—photons.)

Quantum energy: energy contained in a quantum of radiation and proportional to the frequency of the radiation waves. (The energy E of a quantum of radiation of frequency ν is $h\nu$ where h is Planck's constant.)

Rad: unit of absorbed dose. It is 100 ergs per gramme. (See "Absorbed dose".)
Millirad (mrad): 1/1000 rad.

Radiation:

(1) *Primary radiation:*
  (*a*) *X rays:* radiation coming directly from the target of the X-ray tube. Except for the useful beam, the bulk of this radiation is absorbed in the tube housing.
  (*b*) *β and γ rays:* radiation coming directly from the radioactive source.

(2) *Secondary radiation:* radiation, other than the primary radiation, emitted by any matter irradiated with X rays, γ rays, electrons, neutrons, etc. It may consist of X rays, γ rays, electrons, protons, neutrons, etc., or ultraviolet or visible radiation.

(3) *Scattered radiation:* radiation which, during passage through a substance, has been deviated in direction. It may also have been modified by an increase in wavelength (Compton effect). It is one form of secondary radiation.
  (*a*) *Side scattered radiation:* radiation which is scattered in directions approximately at right angles to the direction of the primary beam.
  (*b*) *Back scattered radiation:* radiation which is scattered in directions approximately opposite to the direction of the primary beam.

(4) *Useful beam:* that part of the primary and secondary radiation which passes through the aperture, cone or other device for collimating the X-ray beam.

(5) *Leakage radiation:* in the case of X rays all radiation, except the useful beam, coming from within the X-ray tube and tube housing. (See "Primary radiation".)

(6) *Stray radiation:* radiation not serving any useful purpose. It includes leakage radiation, and secondary radiation from irradiated objects and represents the portion of the radiation against which special protective measures have to be taken.

Radiation hazard: the danger to health arising from exposure to ionizing radiation. It may be due to external radiation or to radiation from radioactive materials within the body.

Radiation-safety officer: a person directly responsible for the safety of all persons in a radiological department. This individual should have the authority to stop operations whenever he believes that the health of workers in his department is being endangered.

Radiation survey: an investigation of those factors associated with an installation or process which could give rise to a radiation hazard.

Radioactivity: spontaneous disintegration of an unstable nuclide with the emission of a particle or a photon, to form a different nuclide.

Radiological department: department or area in a medical, industrial or research organisation where there is a potential radiation hazard.

Relative biological effectiveness (R.B.E.): see report of Sub-Committee I, Section II.4(*c*) and Table B.I.

Rem: see report of Sub-Committee I, Section II.4(*d*).

Millirem: 1/1000 rem.

Röntgen (r): unit of dose of X and γ rays, but not other ionizing radiation. Defined as below:

"The röntgen shall be the quantity of X- or γ-radiation such that the associated corpuscular emission per 0·001293 g of air produces, in air, ions carrying one electrostatic unit of quantity of electricity of either sign." (It becomes increasingly difficult to measure the dose in röntgens as the quantum energy of X- or γ-radiation approaches very high values. The unit may, however, be used for most practical purposes for quantum energies up to 3 MeV. See I.C.R.U. Recommendations.)

Milliröntgen (mr): 1/1000 r.

Microröntgen (μr): 1/1,000,000 r.

Shall: necessary to guarantee adequate protection against radiation.

Should (is recommended): to apply, whenever practicable, in the interests of minimising dangers.

Site monitoring or surveying: continuous or periodic measurement of the local dose-rate. It is complementary to personnel monitoring (q.v.).

Specific ionization of an ionizing particle: number of ions per unit distance along the path of an ionizing particle. (See report of Sub-Committee I, Section II.4(*b*).)

Tissue dose: absorbed dose when the irradiated medium is tissue.

Tube shutter: a device, generally of lead, fixed to an X-ray tube to intercept the useful beam when desired.

X-ray target: structure subjected to bombardment by accelerated electrons in an X-ray tube or accelerator and from which the main beam of X rays is emitted.

VI. MAXIMUM PERMISSIBLE DOSES

1. *For occupational workers*

Since the Commission's last report was issued in 1950, a review has been made of the available information concerning the effects on human beings of ionizing radiations which arise from sources external to the body or from radioactive materials within the body. Whilst no change is recommended in the basic value of the permissible dose for whole-body irradiation,

it has been necessary to consider, in more detail, the values for partial irradiation of the body. Furthermore, the values for the various permissible levels are now expressed in terms not only of the röntgen and the curie (see reports of Sub-Committees I and II), but of the new unit—the rad—recommended by the I.C.R.U. at the Seventh International Congress of Radiology, July 1953. The I.C.R.P. has also found it convenient to express certain dosage values in terms of the rem. though this unit is not officially recognised by the I.C.R.U.

The Commission found, in 1950, that it was not in a position to make firm recommendations regarding the maximum permissible amounts of radioactive isotopes that may be taken into, or retained by, the body. Whilst much uncertainty still remains regarding the behaviour of radioactive materials in the body, the Commission now recommends values for the maximum permissible body burden and the maximum permissible concentration in air and water of a large number of radioactive isotopes which are encountered in occupational exposures. (See report of Sub-Committee II.) The Commission has also carried out an extensive revision of the recommendations dealing with protection against X rays excited at potentials of 5 kV up to two million volts (report of Sub-Committee III) and has introduced numerical data regarding the permissible levels for high-energy X rays and neutrons (combined report of Sub-Committees IV and V).

Whilst the values proposed for maximum permissible doses are such as to involve a risk which is small compared to the other hazards of life, nevertheless, in view of the incomplete evidence on which the values are based, coupled with the knowledge that certain radiation effects are irreversible and cumulative, it is strongly recommended that every effort be made to reduce exposure to all types of ionizing radiations to the lowest possible level. The Commission will continually review the recommended permissible levels as new information becomes available.

2. *For large populations*

The Commission recommends that, in the case of the prolonged exposure of a large population, the maximum permissible levels should be reduced by a factor of ten below those accepted for occupational exposures.

VII. MAXIMUM PERMISSIBLE DOSE-RATE

The Commission feels that, at the present time, there is not sufficient evidence to indicate, even when the weekly doses do not exceed the recommended permissible levels, at what value (if any) the dose-rate itself assumes importance. Accordingly, the Commission considers that it is not justified in recommending a maximum permissible value for dose-rate, but stresses the importance of further research investigations into this problem.

VIII. GENERAL PRINCIPLES REGARDING WORKING CONDITIONS IN RADIOLOGICAL DEPARTMENTS

1. *Responsibility*

The head of the radiological department shall be responsible for the observance of any regulations, recommendations or codes of practice on radiation protection in operation in his own country and for the instruction of all personnel regarding radiation hazards and methods of control.

A technically competent radiation-safety officer should be appointed, to be specifically responsible for the radiation protection measures in the department.

It is the duty of the workers, upon the instruction of the qualified expert or responsible supervisor, to follow the recommendations and instructions which have been drawn up in the interests of radiation protection; further, to use the protective devices provided for their welfare, and to bring to the notice of those in charge any defect which has been revealed.

2. *Approval of plans of department*

Plans for new or modified radiological departments should be discussed with the appropriate protection organisation or other qualified expert.

3. *Radiation survey of department*

A radiation survey shall be made by the appropriate protection organisation, or other qualified expert, of any new or modified radiological department. Routine operation of such a department shall be deferred until it has been found to comply with the regulations, recommendations, or codes of practice in operation in the country concerned. (See "Radiation monitoring", Item VIII.4(*b*) of this report.)

4. *Personnel tests*

(*a*) *Health surveillance*

All new personnel in radiological work shall have a pre-employment blood examination in addition to any other pre-employment examination. The results of such an examination shall determine the acceptance or refusal of the potential employee in radiological work. Notes should be made of the family history, of the occupational professional history, of any unusual radiation exposure during previous occupations, and of any doses previously received as a result of X-ray diagnostic examinations or radiation therapy (including infancy and childhood).

Blood counts should include a red-cell count, haemoglobin and total and differential white-cell count. A note should be made of any abnormal cells. Some haematologists believe that persons whose average total number of white cells is less than 4000/mm^3 (based on two or three counts) should not be employed in a radiological department; others believe that this should not have any influence on the employment or non-employment of persons in departments where they may be exposed to permissible levels of irradiation. In this connection, the physiological variations in white-cell counts and the possible large day to day variations (about 15 per cent) in normal unexposed persons should be borne in mind.

(i) *Pre-employment blood count*

In doubtful borderline cases of abnormality, the blood count should be repeated on successive days or at intervals of a few days.

(ii) *Routine blood count*

Provided that radiation monitoring (both site monitoring and personnel monitoring) is carried out in all circumstances involving occupational exposure to ionizing radiations (external or internal), then

(*A*) routine blood counts are unnecessary in the case of workers who receive doses not exceeding one-third of the permissible doses;

(*B*) routine blood counts are optional in the case of workers who receive doses between one-third and two-thirds of the permissible doses; and

(*C*) routine blood counts are desirable in the case of workers who receive doses exceeding two-thirds of the permissible doses.

(iii) *Blood count technique*

Since the individual trend in blood counts may be of great importance, the technique employed shall be standardised and all observations made under similar conditions.

(iv) *Dismissal of worker*

Abnormal effects indicated by the haematological test should be discussed with a radiologist and a haematologist before any action is taken involving suspension or dismissal from radiological work.

(*b*) *Radiation monitoring*

(i) *External radiation*

The doses of external radiation (for example, X-, β- or γ-radiation) received by personnel should be checked, either continuously or periodically, depending on the circumstances. For the tests, film badges or ionization chambers may be used. If, as a result of the initial radiation survey, the person in charge of the department is satisfied that the doses received by his staff can never exceed the maximum permissible dose, periodic personnel monitoring should suffice. When, however, the safety of personnel depends upon the adherence to a particular technique or the proper functioning of equipment rather than upon low-level sources of radiation or the provision of permanently installed protective barriers, continuous monitoring should be carried out.

(ii) *Internal radiation*

Where unsealed radioactive isotopes are used, environmental surveys with specially-designed equipment may be necessary, if the quantities involved are such as to be potentially hazardous.

(*c*) *Exemptions*

Where conditions as revealed by site monitoring are such that the weekly dose cannot be greater than one-tenth of the permissible dose for external and internal radiation, personnel tests are not necessary.

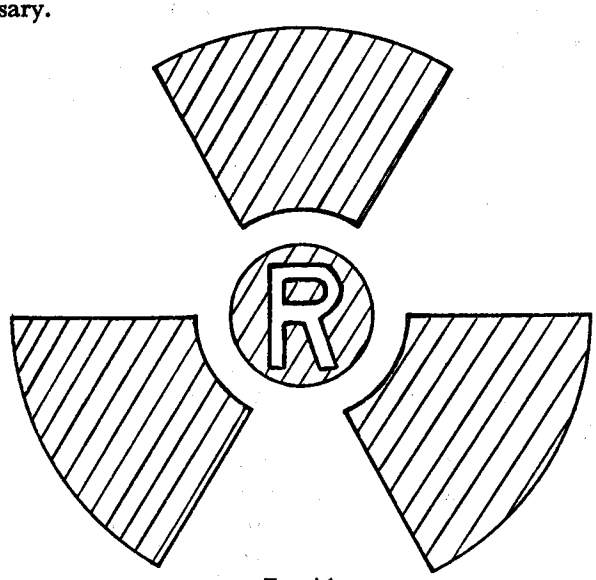

FIG. A1.

Radiation warning sign.

(Various symbols are at present used to indicate a radiation hazard. There are also variations of the above symbol, for example, radial or wave-shaped arrows sometimes point outwards from the centre circle, and the words "radium", "radiation", or "contamination", etc., appear above or below the symbol.)

5. *Radiation warning signs*

In the case of irradiated space, some form of warning shall be provided to indicate the existence of a radiation hazard, even if this is of a temporary nature only. The warning sign may take the form of a lamp which automatically lights up when an X-ray tube is excited or it may be a notice of the type shown in Fig. A1.

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W. Binks (Secretary)
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B. REPORT OF INTERNATIONAL SUB-COMMITTEE I ON PERMISSIBLE DOSE FOR EXTERNAL RADIATION

I. PROTECTION CRITERIA

The recommendations made in this report apply to adults occupationally exposed to ionizing radiation and are based on information at present available. They should not be regarded as permanent. For this reason and on general grounds it is strongly recommended that exposure to radiation be kept at the lowest practicable level in all cases.

In formulating the recommendations emphasis has been placed on the deleterious effects of ionizing radiation manifestable in the lifetime of the individual. Genetic changes possibly injurious to the race as a whole in future generations have been considered, but under present conditions they do not constitute the limiting factor in setting up permissible levels of occupational exposure.

It is obvious that any significant departure from the environmental conditions in which man has evolved may entail a risk of possible deleterious effects. Strictly speaking, therefore, it must be assumed that long continued exposure to ionizing radiation at a dose rate higher than that due to the natural radioactivity of the earth and cosmic rays, involves some risk. Since no radiation level higher than the natural background can be regarded as absolutely "safe", the problem is to choose a practical level that, in the light of present knowledge, involves a negligible risk. It is appropriate to call this a "permissible" level, which for convenience is expressed as a permissible weekly dose.

1. *Permissible dose.* Permissible dose is a dose of ionizing radiation that, in the light of present knowledge, is not expected to cause appreciable bodily injury to a person at any time during his lifetime. As used here "appreciable bodily injury" means any bodily injury or effect that a person would regard as being objectionable and/or competent medical authorities would regard as being deleterious to the health and well-being of the individual. "Dose" is used here more particularly as tissue dose in the irradiated tissue, organ, or region of interest. What constitutes the region of interest depends on the conditions of exposure and must be taken into account in assigning numerical values to the permissible dose or doses applicable to a given set of conditions.

2. *Permissible weekly dose.* Permissible weekly dose is a dose of ionizing radiation accumulated in one week of such magnitude that, in the light of present knowledge, exposure at this weekly rate for an indefinite period of time, is not expected to cause appreciable bodily injury to a person at any time during his lifetime. One week as used here means any seven consecutive days, not a calendar week. All clarifying remarks made in connection with the definition of permissible dose apply to the present case also.

3. *Critical organs and effects.* In the past, occupational exposure has been limited largely to X rays and the permissible weekly dose has been expressed in terms of air dose or surface dose in röntgens. Extension to other types of ionizing radiation necessitates consideration of the doses actually received by different organs of the body. Experience has shown that certain organs are particularly

vulnerable. The following organs are considered critical from the point of view of protection:

Skin
Blood-forming organs
Gonads with respect to impaired fertility
Eyes with respect to cataracts

4. *Dose in an organ.* Some organs, such as the blood-forming organs, are widely distributed in the body and it is difficult to decide what constitutes the organ dose. Obviously an averaging process is involved whereby, at every point of the organ, account is taken of the local dose and its potentiality for harm to the organ. This is unpractical if not impossible, but it may be taken as the ideal to be approached by suitable approximations.

When the whole body is irradiated, a rough approximation of the dose in the organ may be made on the basis of an average or effective depth of the organ below the surface of the skin. For purposes of calculation the following effective depths for the critical organs are suggested:

Skin (basal layer of epidermis)—7 mg/cm^2
Blood-forming organs—5 cm
Ovaries—7 cm
Testes—variable, depending on conditions of exposure
Minimum—1 cm
Lens of the eye—3 mm

When the spatial distribution of radiation in the organ is very non-uniform, an average of the physical dose is not necessarily indicative of the potential damage to the organ in its relation to the normal physiological functions of the body as a whole. Therefore, in such cases it is necessary to consider a local volume within the organ in which the dose is highest. This may be called the significant volume.

For the skin the significant area may be taken to be of the order of a square centimetre in the region receiving the highest dose.

For the blood-forming organs the significant volume may be taken to be of the order of a cubic centimetre in the body region receiving the highest dose.

For the gonads the significant volume may be taken to be 10 per cent of the total volume of both in the region receiving the highest dose.

For the lens of the eye the significant volume is that in which the cell nuclei are located.

II. BASIC PERMISSIBLE WEEKLY DOSES FOR THE CRITICAL ORGANS

1. *Whole-body exposure to X- and γ-radiation expressed in röntgens.* In the light of present knowledge the following values of permissible weekly doses for the critical organs are thought to be well below the limits indicated by the definition of permissible weekly dose.

Skin—600 mr/week in the basal layer of the epidermis in a significant area.

Blood-forming organs—300 mr/week average in a significant volume.

Gonads—300 mr/week average in a significant volume.

Eyes—300 mr/week in a significant volume (essentially at any point in the lens).

2. *Basic dose distribution in the body.* Under certain conditions of occupational exposure to ionizing radiation in general, it is possible to obtain peculiar distributions of radiation in the body, whereby certain tissues may receive relatively large doses of radiation, even when the critical organ doses are

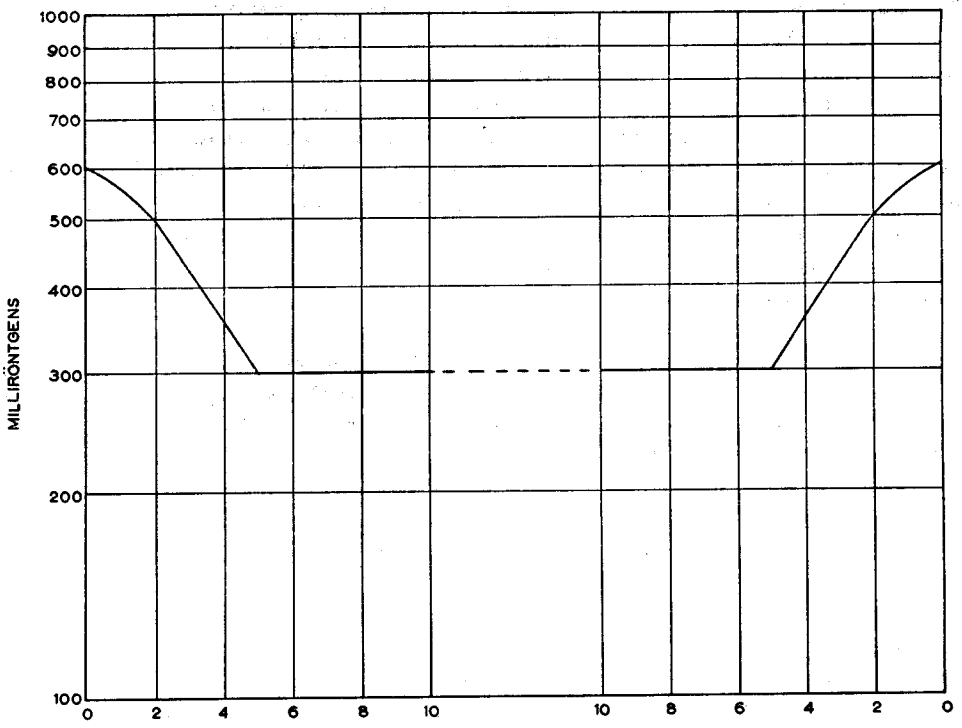

FIG. B1.
Basic dose distribution in the body.

below the permissible limits. To take care of this situation, the permissible dose distribution shown in Fig. B1 has been set up as an arbitrary practical standard. The curve gives the permissible weekly doses in röntgens for tissues at different depths from the skin in the main portion of the body, irrespective of the orientation of the radiation. It is assumed that the effective depth of the blood-forming organs is 5 cm, and therefore the permissible weekly dose at this depth is set at 300 mr.

3. *Whole-body exposure (expressed in rads) to X rays with photon energies less that 3 MeV.* The absorbed dose in rads for each critical organ or tissue at a given depth is approximately that produced by the dose in röntgens in the particular organ or tissue.

For the purposes of this report it shall be assumed that the organ dose or tissue dose in rads is numerically equal to the dose in röntgens in the particular organ or tissue.

4. *Whole-body exposure to radiation of any type or types*

(*a*) *Transition to other photon energies and other types of radiation: guiding principle.* The potential risk of exposure to radiation of any type and energy should not be greater than that involved in exposure to X rays up to 250 kV under comparable conditions.

(*b*) *Specific ionization or linear energy transfer in an organ.* The linear density of the ions along the path of an ionizing particle varies as the square of its charge and is a complicated function of its speed. Light and heavy particles can have the same specific ionization. However, in most cases of practical interest, dense ionization is associated with heavy particles (protons, deuterons, α particles,

etc.). Therefore, large differences in specific ionizations occur in general between X rays and β rays on the one hand and heavy particle radiation on the other. In either case one must deal with some average value or values of the specific ionization in a tissue. This is due to the fact that in general the ionizing particles traversing a small region in a tissue have different specific ionizations, and the energy spectrum of the particles changes from point to point in the tissue.

In practice, the biological effectiveness of a tissue dose delivered by electrons (β rays, or secondary electrons in the case of X rays) does not vary much over the common energy range. Therefore, for protection purposes, it may be assumed that all β rays and X rays have the same biological effectiveness. The specific ionization of very high energy heavy ionizing particles (protons, deuterons, α particles, etc.) may be as low as that of electrons. In that case the biological effectiveness is comparable to that of electrons. Accordingly, the distinction in biological effectiveness must be based on specific ionization rather than on type of ionizing particle. Since most of the directly applicable information on protection has been obtained from the occupational exposure of radiologists and technicians to ordinary X rays up to 250 kV, it is desirable to use this X-ray energy range as a point of reference—especially since the specific ionization in this range is nearly constant. A good round figure for the specific ionization in question is 100 ion pairs per micron of water* (or soft tissue) in terms of its air equivalent. Therefore, all ionizing radiations with specific ionization less than 100 ion pairs per micron of water in the tissue region of interest shall be assumed to have a biological effectiveness of 1.

The number of ion pairs per unit length of track is generally determined in air. In radiology and radiation protection problems, however, one is interested in the transfer of energy to tissues, which includes the energy required to produce ions and the energy imparted to other atoms and molecules that are not ionized but become "excited". It is, therefore, more appropriate to speak of "linear energy transfer per unit length" (LET) than specific ionization. Since in practice values of LET are generally derived from the specific ionization in air, the distinction between the two is essentially a formal one in the present state of the art. In this report "specific ionization" is used because it is more generally understood. It is expressed in ion pairs per "micron of water", although the number of ion pairs really refers to the equivalent path in air, taking account of differences in composition and, if need be, of differences in density when there is a polarisation effect of matter (Fermi).

(*c*) *Conversion factors for other specific ionization; relative biological effectiveness.* When the specific ionization of the ionizing particles is more than 100 ion pairs per micron of water, it is necessary to

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* The average specific ionization of about 100 ion pairs per micron of water for 200 kV X rays is *the value generally quoted in the literature.* D. V. McCormack and H. E. Johns (*Brit. Journ. Rad.*, 1952, xxv, 369) have pointed out that the value obtained depends on the method of calculation. For 200 kV X rays they obtained a "mean ion density" of 55 ion pairs per micron of water by dividing the total number of ion pairs per cubic centimetre by the total range (in microns) of the secondary electrons produced per cubic centimetre. They also calculated an "average ion density" of 102 ion pairs per micron for the same X rays, based on a mean initial energy of 14 keV for the secondary electrons liberated in water. This value agrees with the value used in the present report, but the authors point out that the lower value is the one that should be used. The subject is also discussed by John W. Boag in National Bureau of Standards Report 2946 on "The Relative Biological Efficiency of Different Ionizing Radiations". It is obvious that when the matter is finally settled the numerical value of the specific ionization of 200 kV X rays may be found to be quite different from the one of 100 used in this report. For this reason it would be better at this time not to use specific ionization (or LET) in numerical terms as the basis for the R.B.E. values given in Table B1. On the other hand, it is no longer possible to assign R.B.E. values to "protons", "α particles", etc., because at the very high energies now available, the specific ionizations of these particles approach those of electrons. The uncertainty as to the true value of the specific ionization is greatest in the ordinary X-ray region. Fortunately, in this region there is little change in specific ionization, no matter how it is calculated, and experiments have shown that there is little change in R.B.E. This is the reason why in this report an R.B.E. of one has been assigned to electrons, positrons, and X rays of any energy. This "lumping process" will not be changed by any new determinations of specific ionization, although it may be changed by the accumulation of better knowledge of the *biological* effects of radiation. The calculation of "average" or "mean" specific ionization of heavy particles is simpler and the numerical values are not expected to be materially changed in the future.

consider another factor, the relative biological effectiveness (R.B.E.). The factor R.B.E. stands for the appropriate value of the biological effectiveness of the radiation in question relative to that of X-radiation with an average specific ionization of 100 ion pairs per micron of water, for the particular biological system and biological effect under consideration and for the condition under which the radiation is received.

For the purposes of this report it may be assumed that the values of the R.B.E. given in Table B.I apply to all conditions of external exposure, all tissues and effects of interest. In special cases in which the R.B.E. is definitely known the appropriate generally accepted value may be used.

When it is necessary to add the doses of different radiations received, it may be convenient to introduce another unit, the rem.

(*d*) *The rem.* The rem is the absorbed dose of any ionizing radiation which has the same biological effectiveness as one rad of X-radiation with average specific ionization of 100 ion pairs per micron of water, in terms of its air equivalent, in the same region.

A dose in rems is equal to the dose in rads multiplied by the appropriate R.B.E.

TABLE B.I

R.B.E. VALUES

The following values of R.B.E. for all the critical organs according to the value of the average specific ionizations occurring in the critical organ in which it is highest, are recommended for the determination of permissible tissue doses in rads from external sources by the relation:

$$\text{Permissible dose in rads} = \frac{\text{Permissible dose in rems}}{\text{R.B.E.}}$$

The specific ionization is expressed in ion pairs per micron of water in terms of its air equivalent.

R.B.E. is expressed in terms of the pertinent biological effectiveness of ordinary X rays taken as one (average specific ionization of 100 ion pairs per micron of water, or linear energy transfer of 3·5 keV per micron of water).

1. *X rays, electrons and positrons of any specific ionization*

R.B.E. = 1

2. *Heavy ionizing particles*

Average specific ionization (ion pairs per micron of water)	R.B.E.	Average linear energy transfer to water (keV per micron)
100 or less	1	3·5 or less
100 to 200	1 to 2	3·5 to 7·0
200 to 650	2 to 5	7·0 to 23
650 to 1500	5 to 10	23 to 53
1500 to 5000	10 to 20	53 to 175

For practical purposes, an R.B.E. of 10 is applicable to fast neutrons and protons up to 10 MeV and an R.B.E. of 20 to heavy recoil nuclei for whole-body irradiation and the most sensitive critical organs. (See report of Sub-Committees IV and V.)

(*e*) *Extension to all ionizing radiations.* For exposure to any ionizing radiation, the respective permissible weekly doses (or total doses in a period of time, as the case may be) for the different tissues and organs of the body expressed in rems shall be numerically equal to the appropriate permissible X-ray doses expressed in rads.

(*f*) *Total tissue doses.* It shall be understood that, unless stated otherwise, all permissible doses are total doses resulting in the locus of interest from simultaneous or successive exposure to one or more types of radiation from external or internal sources.

TABLE B.II

BASIC PERMISSIBLE WEEKLY DOSES FOR WHOLE-BODY EXPOSURE TO IONIZING RADIATION OF ANY TYPE OR TYPES

Tissue	Basic permissible weekly dose in the organ* (in mrems)
Skin	600
Blood-forming organs ..	300
Gonads	300
Lens of the eye	300
Other organs and tissues ..	(Basic dose distribution)

* See pages 16 and 17.

These figures shall be regarded as maximum permissible weekly doses except when modifying factors apply (see below).

III. FACTORS MODIFYING THE BASIC PERMISSIBLE WEEKLY DOSES

Practical considerations make it desirable to recommend maximum permissible doses that differ materially from the basic permissible doses, in cases in which this may be done without appreciably increasing the risk. Some special cases are considered below according to modifying factor.

1. Electromagnetic radiation only (up to 3 MeV).
   Whole-body exposure.
   (*a*) 300 mr/week measured in air.
   (*b*) Gonad dose not to exceed 300 mr/week.
2. Radiation of very low penetrating power. (H.V.L. less than 1 mm of water.)
   Whole-body exposure.
   (*a*) Skin—1500 mrems/week.
   (*b*) Lens of eye—300 mrems/week.
3. Limited portion of body.
   (*a*) Hands and forearms—1500 mrems/week in the skin. Less in deeper tissues.
   (*b*) Feet and ankles—1500 mrems/week in the skin. Less in deeper tissues.
   (*c*) Head and neck—1500 mrems/week in the skin. 300 mrems/week in the lens of the eye. Less than 1500 mrems/week in deeper tissues.
   (*d*) In all these cases the skin dose refers to the significant skin area receiving the highest weekly dose.

IV. TEMPORARY EXPOSURE

Since it is generally impossible to predict how long a person may be occupationally exposed to radiation, it is prudent to assume that it may continue throughout his life. Therefore, "temporary"

exposure at levels higher than the permissible weekly dose should not be permitted. If it does occur it must be assumed in general that it alters unfavourably the radiation tolerance status of the individual and measures tending to restore it to normal shall be initiated as soon as practicable, in accordance with the recommendations of competent experts.

V. DETERMINATION OF TISSUE DOSES AND ACCURACY

Measurement in röntgens of air doses or doses in a patient or "phantom" should be made under the conditions existing in the locus of interest, with instruments that permit the evaluation of the energy imparted to the tissue in question by the ionizing particles of the radiation.

Since it is not always practicable to make such measurements, tissue doses in rads may be determined indirectly. In such cases the methods and constants used should be those generally accepted by experts in this field at the time of interest.

The accuracy of measurements or indirect determinations of tissue doses shall be as high as accepted practice permits at the time of interest. At any rate, proper allowances for possible errors shall be made to make sure that the actual doses to be received by a person cannot exceed the maximum permissible limits.

Members of International Sub-Committee I presenting the above report.

G. Failla (Chairman)
L. Bugnard
D. G. Catcheside
J. F. Loutit
H. J. Muller
R. M. Sievert
R. S. Stone
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C. REPORT OF INTERNATIONAL SUB-COMMITTEE II ON PERMISSIBLE DOSE FOR INTERNAL RADIATION

I. INTRODUCTION

The purpose of this report is to list recommended values of maximum body burden and maximum concentration in air and water of the various radioisotopes that are considered permissible for occupational exposure. Appropriate values depend upon the physical condition of the individual exposed, the physical and chemical properties of the radioactive material and the method of body intake—ingestion, inhalation, through wounds or direct absorption through the skin. Therefore, in order to limit the scope of this international report on internal dose, only general maximum permissible concentration values for soluble or insoluble compounds are considered; the only methods of body intake referred to in the tables are ingestion and inhalation; and all calculations are referred to the so-called "standard man" in whom all characteristics are assumed to be those representative of the average man.

Ideally, one would prefer to select maximum permissible body burdens and maximum permissible concentration values that are based on observations on humans who have consumed the particular radioactive material under the conditions and over a period of time approximating those set forth as being applicable to the maximum permissible values selected. Only in the case of radium, however, does one have an accumulation of human experience over a period of years that is suitable to serve as a basis of selection of these values. In a few cases the chemical behaviour of other elements is sufficiently similar to that of radium so that comparisons with radium may serve as a basis of choice of maximum permissible values. Usually, however, human data are lacking completely for a particular radioisotope and in such cases data from limited animal experiments must be extrapolated to man. Sometimes even animal data are not available and in such cases estimates are made from a comparison with elements having similar chemical properties and/or from an investigation of the body retention, distribution and elimination of stable isotopes of the radio-element under consideration. In the case of all bone-seeking radioisotopes (with the exception of Ra, ^{32}P and radioisotopes that emit only X- or γ-radiation) a factor of safety of 5 is applied to the calculations to take into account the uneven distribution of the radioactive material within the bone, but for other critical body organs uniform distribution is assumed and the maximum permissible values are based on a calculation of that burden in the body that will result in an average dose of ionizing radiation to the critical body organ of 0·3 rem/week. It is recognised that calculations based on average dose or uniform distribution in the critical body organ may lead to considerable error since some radioisotopes are unevenly deposited. Although the average dose to the critical organ may be 0·3 rem/week, some portions of the organ may receive considerably less than this average exposure, while others correspondingly more. However, the choice of 0·3 rem/week as a maximum weekly permissible tissue dose is based more on what is considered to be an acceptable weekly exposure to the entire body or to the blood-forming organs than on a permissible weekly exposure to a small element of tissue. On this basis, plus the fact that there are other assumptions made in the calculations

leading to probable errors of the same order of magnitude, it appears that detailed refinements in the calculations (*e.g.* taking into account the unequal distribution within a body organ) are not justified in many cases.

In spite of the limitations of these data it is believed that these values should serve a useful purpose because many persons are being exposed to these radioactive materials at present, and these tables should be a guide to indicate whether or not sufficient measures are being taken to limit the internal dose from radioactive materials. On the same score it is considered wise to avoid all unnecessary exposure to radioisotopes. Unlike external exposure, which usually lasts for only a short period of time, internal exposure due to a body burden of a radioisotope may last for many months or even a lifetime. Also, once radioactive contaminants become fixed in the body it is difficult to make an accurate estimate of the distribution in the body or of the total body burden. Following accepted practice in the industrial and public health field, and keeping in mind the uncertainties involved and the fact that in the future some of the values given in this report may be lowered, it is recommended, in the case of prolonged exposure of a large population, to reduce by a factor of 10 the permissible level for radioactive isotopes accepted for occupational exposures. The values given in this report are for occupational exposure and are understood to be additional to natural background. Exposure for a lifetime at the maximum permissible values recommended in this report is not expected, in the light of present knowledge, to cause appreciable body damage. The application of the safety factor of 10 will reduce the risks of genetic damage that are a consequence of a large average exposure to the population.

II. THE STANDARD MAN

When efforts were first made to establish maximum permissible body burdens and the maximum permissible concentration values for the various radioisotopes, it soon became evident that it would be difficult, if not impossible, to compare suggested values from the various laboratories unless all used the same basic assumptions relative to the average man. Most of the calculations were based on the same fundamental physical assumptions relative to the energy schemes and radioactive half-lives of the radioisotopes, but each person making these calculations used his own preferred values for the mass and effective radius of the body organs, the rates of ingestion and inhalation, elimination rates, etc. This difficulty was recognised at the Chalk River Conference on Permissible Dose,[1] and later at the Sixth International Congress of Radiology,[2] the Harriman Conference on Permissible Dose,[3] and the Seventh International Congress of Radiology,[4] and as a consequence certain characteristics of this so-called "standard man" were agreed upon. The values listed in Tables C.I, C.II and C.III are those agreed on at the Chalk River Conference and later modified at the conferences in London, Harriman and Copenhagen. These values are used in calculations in this report except where other data are available for a specific radioisotope. Many of the values given in these tables do not agree with some published data and much fundamental information is lacking. However, in most cases and in spite of these limitations, these tables have served the useful function of reducing calculations to a common denominator where immediate comparisons can be made.

[1] Chalk River Conference on Permissible Dose. A conference of representatives from the United Kingdom, Canada and the United States, meeting in Chalk River, Canada, September 29 and 30, 1949.

[2] International Recommendations on Radiological Protection as revised by the International Commission on Radiological Protection at the Sixth International Congress of Radiology meeting in London, July 1950. *Brit. Journ. Rad.*, January 1951, xxiv, 277, and as Handbook 47 by the U.S. Department of Commerce.

[3] Harriman Conference on Permissible Dose. A conference of representatives from the United Kingdom, Canada and the United States, meeting at Harriman, New York, March 30 and 31, and April 1, 1953.

[4] Seventh International Congress of Radiology and associated conferences of the International Commission on Radiological Protection, meeting in Copenhagen, Denmark, July 13–24, 1953.

TABLE C.I

AVERAGE CHEMICAL COMPOSITION OF THE ADULT HUMAN BODY

Element		Per cent by weight	Approximate amount in a 70 kg man (g)
Oxygen	O	65·0	45,500
Carbon	C	18·0	12,600
Hydrogen	H	10·0	7,000
Nitrogen	N	3·0	2,100
Calcium	Ca	1·5	1,050
Phosphorous	P	1·0	700
Sulphur	S	0·25	175
Potassium	K	0·2	140
Sodium	Na	0·15	105
Chlorine	Cl	0·15	105
Magnesium	Mg	0·05	35
Iron	Fe	0·006	4
Copper	Cu	0·0002	0·1
Manganese	Mn	0·00003	0·02
Iodine	I	0·00004	0·03

TABLE C.II

MASS AND EFFECTIVE RADIUS OF ORGANS OF THE ADULT HUMAN BODY***

	Mass, m, (g)	Per cent of total body*	Effective radius, X (cm)
Total body*	70,000	100	30
Muscle	30,000	43	30
Skin and subcutaneous tissue**	6,100	8·7	0·1
Fat	10,000	14	20
Skeleton: Without bone marrow	7,000	10	5
Red marrow	1,500	2·1	
Yellow marrow	1,500	2·1	
Blood	5,400	7·7	
Gastrointestinal tract*	2,000	2·9	30
Contents of G.I. tract—			
Lower large intestine	150		5
Stomach	250		
Small intestine	1,100		
Upper large intestine	135		
Liver	1,700	2·4	10
Brain	1,500	2·1	
Lungs (2)	1,000	1·4	30
Lymphoid tissue	700	1·0	
Kidneys (2)	300	0·43	7
Heart	300	0·43	
Spleen	150	0·21	7
Urinary bladder	150	0·21	
Pancreas	70	0·10	
Salivary glands (6)	50	0·071	
Testes (2)	40	0·057	
Spinal cord	30	0·043	
Eyes (2)	30	0·043	
Thyroid gland	20	0·029	3
Teeth	20	0·029	
Prostate gland	20	0·029	
Adrenal glands or suprarenal (2)	20	0·029	
Thymus	10	0·014	
Miscellaneous (blood vessels, cartilage, nerves, etc.)	390	0·56	

* Does not include contents of gastrointestinal tract.

** The mass of the skin alone is taken as 2000 g.

*** The reports, "The Standard Man", by Hermann Lisco, ANL-4253, November 1948–February 1949, p. 96, and "A Survey Report of the Characteristics of the Standard Man", September 1948, by M. J. Cook, were used as the principal sources of reference in the original selection of values given in this table.

TABLE C.III

CHARACTERISTICS OF THE STANDARD MAN

	c.c./day
Water intake in food	700
Water intake as fluids	1500
Water intake in food and fluids	2200
Water of oxidation	300
Total water consumption per day	2500
Water excretion as sweat	500
Water excretion from lungs	400
Water excretion by faeces	100
Water excretion by urine	1500
Total water excretion per day	2500
Air inhaled during 8-hour work day	10^7
Air inhaled during 16 hours not at work	10^7
Total air inhaled per day	2×10^7

CO_2 in alveolar air—5·5%

Interchange area of lungs	50 sq. metres
Area of upper respiratory tract, trachea, bronchials	20 sq. metres
Total surface area of respiratory tract	70 sq. metres

Total water in body—50 kg
Average life span of man—70 years
Occupational exposure of man: 8 hours/day, 40 hours/week, and 50 weeks/year
Minimum thickness of epidermis—0·07 mm, and depth of blood-forming organs—5 cm

PARTICULATES IN RESPIRATORY TRACT

Retention of particulate matter in the lungs depends on many factors, such as the size, shape and density of the particles, the chemical form and whether or not the person is a mouth breather; however, when specific data are lacking it is assumed the distribution is as follows:

Distribution	Readily soluble compounds	Other compounds
Exhaled	25%	25%
Deposited in upper respiratory passages and subsequently swallowed	50%	50%
Deposited in the lungs (lower respiratory passages)	25% (this is taken up into the body)	25%*

* Of this, half is eliminated from the lungs and swallowed in the first 24 hours, making a total of 62½% swallowed. The remaining 12½% is retained in the lungs with a half-life of 120 days, it being assumed that this portion is taken up into body fluids.

III. THE CRITICAL BODY ORGAN

In choosing the maximum permissible body burden of a radioisotope the first step is to choose the critical body organ, which is defined as that organ of the body receiving the radioisotope that results

in the greatest damage to the body. In most cases it is that organ of the body that receives the greatest damage, but this does not necessarily follow since some body organs are less essential than others to the well-being of the entire body. Usually the critical organ is the one that accumulates the greatest concentration of the radioactive material, but this does not necessarily follow since there is great variation in the radiosensitivity of the organs. The critical body organ depends upon the method of body intake—ingestion, inhalation, injection, etc.—and may change with time following the intake of the radioactive material. For example, the respiratory tract or the gastrointestinal tract is usually the critical organ if an insoluble compound of a radioactive material is inhaled, but if it enters the body by way of a contaminated wound, the wound site is usually the critical tissue. If soluble compounds of this same radioactive material are inhaled, the upper respiratory or gastrointestinal tract may be initially the critical organ, and, likewise, in case of ingestion the gastrointestinal tract is usually the critical organ during the first day following the body intake. In the intermediate period the critical organ may be the kidney or liver, and frequently the skeleton is the critical organ for chronic exposure. Usually—but not always—the critical body organ for chronic exposure is that body organ having the greatest concentration and frequently it is the organ having the longest biological half-life for the element. The total body becomes the critical organ when the radioelement is rather evenly distributed throughout the body, *e.g.* ^{24}Na, ^{36}Cl and ^{3}H. Sometimes it is uncertain which of several body organs should be selected as the critical organ, and for this reason biological constants for soluble forms of the element are given in Table C.IV for the total body and in most cases for one or two body organs. As a general rule the organ that is subjected to the highest dose-rate for the lowest concentration of the radioisotope in air and water is selected as the critical organ. On this basis the gastrointestinal tract is the critical organ in most cases during the period of ingestion or inhalation of the radioisotope. In such cases, however, other organs become the critical body organs when the intake of the radioisotope is discontinued and, therefore, these additional organs are listed in Tables C.IV, C.V and C.VIII.

IV. DISTRIBUTION FRACTIONS AND RELATED CONSTANTS

Before beginning a calculation of the body burden and the maximum permissible concentration values there are a number of distribution fractions and constants that must be obtained; they are as follows:

1. *Fraction passing from gastrointestinal tract to the blood.* This is given as f_1 and values are listed in column 5 of Table C.IV.

2. *Fraction passing from blood to critical body organ.* This is given as f_2' and values are listed in column 15 of Table C.IV.

3. *Fraction in critical organ of that in the total body.* This is given as f_2 and values are listed in columns 10 and 17 of Table C.IV.

4. *Fraction of that taken into the body that is retained in the critical organ.* This fraction is given by f_a in the case of inhalation and f_w in the case of ingestion.

   For inhalation of soluble material $f_a=(0{\cdot}25+0{\cdot}5\,f_1)\,f_2'$. Sometimes when the value of f_2' is unknown, it is replaced by f_2 as a rough approximation. Values of f_a are listed in columns 6, 12 and 19 of Table C.IV. When the lung is taken as the critical organ, f_a is set equal approximately to $f_a=0{\cdot}25\,(1-f_1)$. In all cases considered in Table C.VIII the estimated dose to the lungs from inhalation of soluble compounds was less than the dose to the gastrointestinal tract. Therefore, these values based on lung as the critical organ were omitted from Table C.VIII.

1	2	3	4	5	6	7	8	9	10	11
Z	Element	Sym-bol	I g/day	TOTAL BODY				CRITICAL ORG		
				f_1	f_a	T_b	C	Name	f_2	f_w
1	Hydrogen	H	250	1·0	0·75	19	0·1	Total body	1·0	1·0
2	Helium	He						Total body		
3	Lithium	Li		1·0		4		Total body		1·0
4	Beryllium	Be		0·01	0·25	123		Bone	0·9	4 × 10
5	Boron	B								
6	Carbon	C	300	0·95	0·72	230	0·18	Fat	0·6	0·5
7	Nitrogen	N					0·03			
8	Oxygen	O					0·65			
9	Fluorine	F	5×10^{-3}	1·0	0·75	1·08		Bone	0·95	0·1
10	Neon	Ne						Total body		
11	Sodium	Na	4	0·95	0·73	19	$1·5 \times 10^{-3}$	Total body	1·0	0·95
12	Magnesium	Mg					0·0005			
13	Aluminium	Al								
14	Silicon	Si								
15	Phosphorus	P	1·4	0·7	0·60	13	0·01	Bone	0·92	0·2
16	Sulphur	S	1·3	0·56	0·53		0·0025	Skin	0·1	0·08
17	Chlorine	Cl	6·7	0·95	0·73	19	$1·5 \times 10^{-3}$	Total body	1·0	0·95
18	Argon	A						Total body		
19	Potassium	K	2·8	0·9	0·70	38	0·002	Muscle	0·75	0·7
20	Calcium	Ca	0·8	0·9	0·70	18000	0·015	Bone	0·99	0·25
21	Scandium	Sc		0·0005	0·25	28		Spleen	0·04	2 × 10
22	Titanium	Ti								
23	Vanadium	V		0·005	0·25	42		Bone	0·5	5 × 10
24	Chromium	Cr	Trace	0·05	0·27	16		Kidneys	0·06	7 × 10
25	Manganese	Mn	4×10^{-3}	0·1	0·3	2·6	3×10^{-6}	Kidneys	0·009	0·004
26	Iron	Fe	0·012	0·8	0·65		4×10^{-5}	Blood	0·64	0·8
27	Cobalt	Co	Trace	0·2	0·35	21		Liver	0·68	0·004
28	Nickel	Ni	Trace	0·2	0·35			Liver	0·68	0·004
29	Copper	Cu	0·002	0·28	0·39		2×10^{-6}	Liver	0·08	0·09
30	Zinc	Zn	0·017	0·1	0·35			Bone	0·15	2 × 10
31	Gallium	Ga		0·001	0·25	5		Bone	0·82	4 × 10
32	Germanium	Ge		0·01	0·25	2		Kidneys	0·35	2 × 10
33	Arsenic	As		0·03	0·26	280		Kidneys	0·02	3 × 10
34	Selenium	Se				23		Kidneys	0·07	
35	Bromine	Br								
36	Krypton	Kr						Total body		
37	Rubidium	Rb		1·0	0·75	13		Muscle	0·54	0·42
38	Strontium	Sr	3×10^{-4}	0·6	0·55	190		Bone	0·7	0·25
39	Yttrium	Y		0·0005	0·25	550		Bone	0·65	3 × 10
40	Zirconium	Zr		0·0005		5000		Bone	0·62	10^{-4}
41	Niobium	Nb		0·45	0·47	73		Bone	0·4	0·13
42	Molybdenum	Mo	Trace	0·7	0·6			Bone	0·5	2 × 10
43	Technetium	Tc		0·5	0·5	0·8		Kidneys	0·1	3 × 10
44	Ruthenium	Ru		<0·0005	0·25	86		Kidneys	0·04	2 × 10
45	Rhodium	Rh		0·2	0·35	18		Kidneys	0·08	0·01
46	Palladium	Pd		0·2	0·35	5		Kidneys	0·5	0·02
47	Silver	Ag		0·02	0·26	2		Liver	0·1	1 × 10
48	Cadmium	Cd		0·0025	0·25	260		Liver	0·8	2 × 10
49	Indium	In				24				
50	Tin	Sn		0·0087	0·25	67		Bone	0·8	0·0026

ENTS IN THE HUMAN BODY*

12	13	14	15	16	17	18	19	20	21
(1st choice)				CRITICAL ORGAN (2nd choice)					
f_a	T_b	C	f_2'	Name	f_2	f_w	f_a	T_b	C
0·75	19	0·1	1·0						
0·09	4 400		0·35	Spleen	0·006	2×10^{-5}		138	
0·36	35	0·75	0·5	Bone	0·07	5×10^{-3}	4×10^{-2}	180	0·13
8×10^{-2}	140	1×10^{-4}	0·1	Teeth	0·1	0·1	8×10^{-2}	140	2 ×
0·73	19	$1·5 \times 10^{-3}$	1·0						
0·2	1600	0·09	0·3						
0·074	22	0·009	0·14						
0·73	19	$1·5 \times 10^{-3}$	1·0						
0·53	37	0·0035							
0·41	18000	0·15	0·58						
8×10^{-3}	15		0·03	Liver	0·6	2×10^{-4}	0·12	15	
0·025	50		0·1						
0·004	110	3×10^{-5}	0·014						
2×10^{-2}	2·5	6×10^{-7}	0·08	Liver	0·16	0·01	0·09	5	2 ×
0·65	65	5×10^{-4}	1·0						
0·007	8·4	2×10^{-7}	0·02	Spleen	0·14	5×10^{-5}	8×10^{-5}	9	5 ×
0·007	8	Trace	0·02						
0·13	39	6×10^{-6}	0·33	Eyes	5×10^{-4}	1×10^{-3}	0·002	21	3 ×
5×10^{-2}	23	1×10^{-4}	0·15						
0·1	3×10^3	$< 1 \times 10^{-6}$	0·4						
5×10^{-3}	6		0·02						
3×10^{-3}	37		0·01	Bone	0·04	9×10^{-4}		120	
	3		0·03						
0·33	13		0·44						
0·22	4×10^3	6×10^{-5}	0·4						
0·14	>500		0·55	Lungs	0·004	2×10^{-6}		34	
0·058	180		0·23						
0·12	50		0·25						
2×10^{-4}	150	Trace	3×10^{-4}						
3×10^{-3}	4		0·005						
0·01	20		0·04						
2×10^{-2}	28		0·05						
4×10^{-2}	6		0·1						
2×10^{-3}	3		0·006						
0·19	100		0·75						
			0·02						
0·076	72		0·3	Lungs	0·007	3×10^{-5}		150	

1	2	3	4	5	6	7	8	9	10	11
Z	Element	Sym-bol	I g/day	TOTAL BODY				CRITICAL ORGA		
				f_1	f_a	T_b	C	Name	f_2	f_w
51	Antimony	Sb		0·03		370		Bone	0·25	3 × 10
52	Tellurium	Te		0·25	0·37	1700		Kidneys	0·2	7 × 10
53	Iodine	I	2 × 10^{-4}	1·0	0·75	130	4 × 10^{-7}	Thyroid	0·2	0·2
54	Xenon	Xe						Total body		
55	Cæsium	Cs		1·0	0·75	25		Muscle	0·45	0·48
56	Barium	Ba		0·1	0·35	120		Bone	0·96	0·07
57	Lanthanum	La		0·003	0·25	23		Bone	0·3	1 × 10
58	Cerium	Ce	Trace	0·0005	0·25	330		Bone	0·8	2 × 10
59	Praseodymium	Pr		0·005	0·25	420		Bone	0·6	1 × 10
60	Neodymium	Nd		0·0005		47		Bone	0·4	
61	Promethium	Pm		0·0005	0·25	48		Bone	0·7	2 × 10
62	Samarium	Sm		0·0001	0·25	5		Bone	0·65	3 × 10
63	Europium	Eu		0·0005	0·25	360		Bone	0·7	2 × 10
64	Gadolinium	Gd								
65	Terbium	Tb				340		Bone	0·9	
66	Dysprosium	Dy								
67	Holmium	Ho		0·12	0·31	33		Bone	0·5	<1 × 10
68	Erbium	Er								
69	Thulium	Tm		0·0005	0·25	360		Bone	0·92	4 × 10
70	Ytterbium	Yb		0·25		18		Bone	0·45	0·0001
71	Lutetium	Lu		0·0005	0·25	6		Bone	0·5	2 × 10
72	Hafnium	Hf						Spleen	0·03	
73	Tantalum	Ta		0·0005		150		Liver	0·5	2 × 10
74	Tungsten	W		0·1				Bone	0·65	0·008
75	Rhenium	Re		0·5	0·50	7		Thyroid	0·005	1 × 10
76	Osmium	Os								
77	Iridium	Ir		0·2	0·35	13		Kidneys	0·15	0·01
78	Platinum	Pt		0·1				Kidneys	0·26	0·011
79	Gold	Au	Trace	0·1	0·30	12		Kidneys	0·06	0·024
80	Mercury	Hg						Kidneys	0·84	
81	Thallium	Tl		0·45				Muscle	0·51	0·24
82	Lead	Pb	3 × 10^{-4}	0·15	0·32			Bone	0·8	5 × 10
83	Bismuth	Bi				3		Liver	0·48	
84	Polonium	Po		0·03	0·26	100		Spleen	0·06	6 × 10
85	Astatine	At		1·0	0·75	27		Thyroid	0·2	0·07
86	Emanation	Em						Lungs	1	
87	Francium	Fr								
88	Radium	Ra	7 × 10^{-13}	0·2	0·35	2 × 10^4		Bone	0·99	0·015
89	Actinium	Ac		<0·003		430		Bone	0·9	0·009
90	Thorium	Th		0·0005	0·25	180		Bone	0·82	4 × 10
91	Protoactinium	Pa		0·0005		270		Bone	0·65	2 × 10
92	Uranium	U	2 × 10^{-6}	0·0005	0·25			Kidneys	0·065	2 × 10
93	Neptunium	Np		0·0005		42		Bone	0·93	5 × 10
94	Plutonium	Pu		0·0001	0·25			Bone	0·75	1 × 10
95	Americium	Am		0·0005	0·25	1100		Bone	0·9	1 × 10
96	Curium	Cm		0·0005	0·25	440		Bone	0·9	1 × 10
97	Berkelium	Bk								
98	Californium	Cf								

* The values given for f_1, f_2', f_w, f_a and T_b are for soluble compounds with exception of cases where the lungs are given as the critical orga

I = normal daily intake of element (g/day).
f_1 = fraction going from gastrointestinal tract to the blood.
f_2 = fraction in critical organ of that in total body.
f_2' = fraction going from blood to critical organ.
f_w = fraction taken orally that arrives in critical organ.
f_a = fraction inhaled that is retained in critical organ.
T_b = Biological half-life or time required for removal of h of the element from the organ by biological processes (day
C = concentration in organ $\left(\frac{\text{g of element}}{\text{g of tissue}}\right)$.

C.IV (*continued*)

ENTS IN THE HUMAN BODY*

12	13	14	15	16	17	18	19	20	21
(1st choice)				CRITICAL ORGAN (2nd choice)					
f_a	T_b	C	f'_2	Name	f_2	f_w	f_a	T_b	C
	5		0·01						
0·02	15		0·06						
0·15	120	$3·5 \times 10^{-4}$	0·2						
0·36	17		0·48						
0·2	~200		0·7						
0·1	35		0·4						
0·1	500	Trace	0·4						
0·063	50		0·25						
	35		0·35						
0·09	100		0·35						
0·05	4×10^4		0·2	Spleen	0·006	4×10^{-7}		5	
0·09	1400		0·35	Spleen	0·004	2×10^{-6}		850	
	170		0·6						
0·07	37		0·22						
0·18	110		0·7						
			0·32						
0·075	6		0·3						
	10		0·15						
0·075	130		0·3	Lungs	(1·0)		(0·08)	10	
0·024	5		0·08						
1×10^{-3}	0·5		0·0025	Skin	0·8	0·12	0·12	5	
2×10^{-3}	23		0·05	Spleen	0·08	3×10^{-4}	0·006	130	
0·033	64		0·11						
0·072	50	Trace	0·24	Liver	0·98	0·0098	0·25	50	
0·26	17		0·06						
0·098	<730	2×10^{-6}	0·3						
			0·35	Kidneys	0·3			2	
0·004	57		0·02	Lungs	(1·0)		(0·12)	(40)	
0·05	180		0·07						
				Total body					
0·026	2×10^4	2×10^{-14}	0·075						
	1200		0·3	Kidneys	0·003	9×10^{-6}		110	
0·2	4×10^4		0·78						
	400		0·45						
0·08	30	2×10^{-8}	0·33	Bone	0·85	10^{-4}	0·05	300	10^{-9}
	100		0·65						
0·18	$4·3 \times 10^4$		0·7	Lungs	(1·0)		(0·12)	(360)	
0·063	890		0·25						
0·063	600		0·25						

References to most of the sources of information used in the selection of values given in the above table may be found in "Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water", National Bureau of Standards Handbook 52, 1953 (Superintendent of Documents, Washington 25, D.C., U.S.A.).

For inhalation of insoluble and slightly soluble material a portion of the gastrointestinal tract or the lung is usually the critical organ. Unless data are available for the specific radioactive dust particles, it is assumed in the case of the lungs that $f_a=0{\cdot}12$. In the case in which some of the radioactive material is swallowed, so that it irradiates a portion of the gastrointestinal tract as the critical tissue, the value of f_a is given by the equation, $f_a=0{\cdot}625\ (1-f_1)$.

For ingestion of soluble compounds $f_w=f_1 f_2'$ and again f_2 is sometimes used in place of f_2' if no better information is available.

For ingestion of insoluble compounds a portion of the gastrointestinal tract is the critical tissue and $f_w=(1-f_1)$.

5. *Factor of non-uniform distribution in the critical organ, N.* This factor N is taken as 5 relative to radium for all α-emitting radioisotopes that are bone-seeking elements. It is taken as 5 for the light particle energy components of nuclear disintegration—β particles, positrons and internally converted electrons—of all bone-seeking radioisotopes (with the exception of ^{32}P) relative to light particle emitting radioisotopes uniformly distributed in the bone in such a manner as to deliver a dose-rate of 0·3 rem/week. This factor N is multiplied by the α, β^-, β^+, e^- and atomic recoil energy components and by the appropriate R.B.E. as indicated by equation 5 and the resulting values of $\Sigma E(\mathrm{RBE})N$ listed in column 5 of Table C.V.
6. *Average daily ingestion of an element, I,* is given in g/day and the values are listed in column 4 of Table C.IV.
7. *Average concentration, C,* of the element in the critical organ is given in g of element per g of critical tissue. Values are listed in columns 8, 14 and 21 of Table C.IV.
8. *Average chemical composition, g,* of the entire body. These values are given in column 3 of Table C.I.

All of the above biological values can be obtained for a number of the radioisotopes from animal experiments and in only a limited number of cases, such as with radium or as a result of a few laboratory accidents with fission products, has it been possible to collect human data. Table C.IV lists values of f_1, f_2, I, f_w, f_a, C, and f_2'. The blank spaces in the table emphasise where biological data are lacking and most of the values that are given are based on very limited data so that they must be revised as more accurate information becomes available. Under conditions of chronic exposure, when an equilibrium distribution and concentration of an element has been built up in the body, it is possible to determine the above values for some of the radioisotopes by making measurements of the stable element distribution. This is done by means of chemical, spectrographic and neutron activation analyses of human tissue and food. It is assumed that a radioactive isotope of an element when taken into the body in the same average chemical composition as the stable isotopes of the element over a long period of time would follow the same distribution pattern as the stable isotopes. For example, under these conditions the value of f_2 for ^{90}Sr would be the same as for stable strontium and

$$f_2=\frac{m\,C}{M} \qquad \text{(C1)}$$

in which m=g of critical organ, C=g element per g of critical organ, and M=g element in total body.

V. EFFECTIVE HALF-LIFE

In this first report of the International Commission on Radiological Protection on "Permissible Dose for Internal Radiation", maximum permissible body burden and maximum permissible concentration values in air and water are determined only for chronic exposure, and in most cases

where a condition of equilibrium is built up in the body. Under equilibrium conditions it is assumed that the dose-rate to the critical body organ is constant at 0·3 rem/week, or the radioisotope entering the critical body organ is exactly equal to the elimination per unit time by radioactive and biological decay as indicated by the upper flat portion of the curves in Fig. C1. In most cases this equilibrium condition is reached in a few weeks, but in some cases where the effective half-life is very long, equilibrium is not reached until after many years, as illustrated by the curve for ^{239}Pu in Fig. C1.

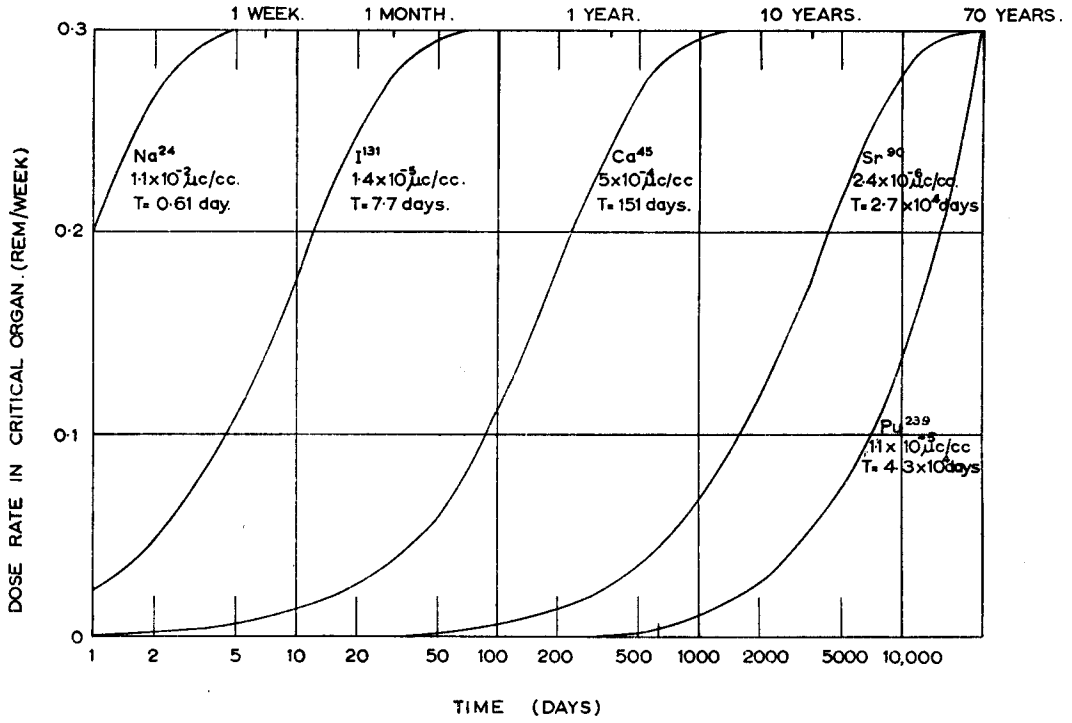

FIG. C1.

The increase in dose-rate to the critical body organ as a result of continuous use of water contaminated with indicated radioisotopes is shown. The curves are plots of equations 7 and 10. The concentrations used in making these plots are given to the right of each curve and differ somewhat from the maximum permissible values listed in column 5 of Table C.VIII, where other factors influenced the actual choice of maximum permissible concentrations.

In no case are the maximum permissible values calculated for a period of exposure greater than 70 years. In this time all the radioisotopes considered in this report have reached equilibrium with the exception of natural thorium, ^{239}Pu, ^{151}Sm and ^{226}Ra, which have reached 34, 34, 36 and 67 per cent of equilibrium respectively. ^{90}Sr, which has the next longest effective half-life, reaches 99 per cent of equilibrium after 49 years. For chronic exposure the effective half-life determines when equilibrium is reached—see Fig. C1—and the concentration of the radioisotope in air or water determines the dose-rate received by the critical body organ when equilibrium is reached.

The effective half-life is given by the equation,

$$T = \frac{T_b\, T_r}{T_b + T_r} \qquad \text{.....(C2)}$$

in which T = effective half-life,

T_r = radioactive half-life,

T_b = biological half-life.

Actually, the biological elimination from the body does not follow a simple exponential decay but a more complex pattern. However, in most cases, after the initial distribution and readjustment of the radioisotope from one body organ to the other, as shown in Fig. C2, the decay curve is usually close to a simple exponential, as indicated by the portion of the curve from b to c. Ideally, except for ethical reasons, one would prefer to obtain this effective half-life from experimental data on humans that have been subjected to continuous exposure, but such data ordinarily are not available. Even chronic exposure animal data, such as indicated in Fig. C1, are seldom to be found, and as a result one usually resorts to the use of acute exposure animal data as indicated in Fig. C2. Such data are

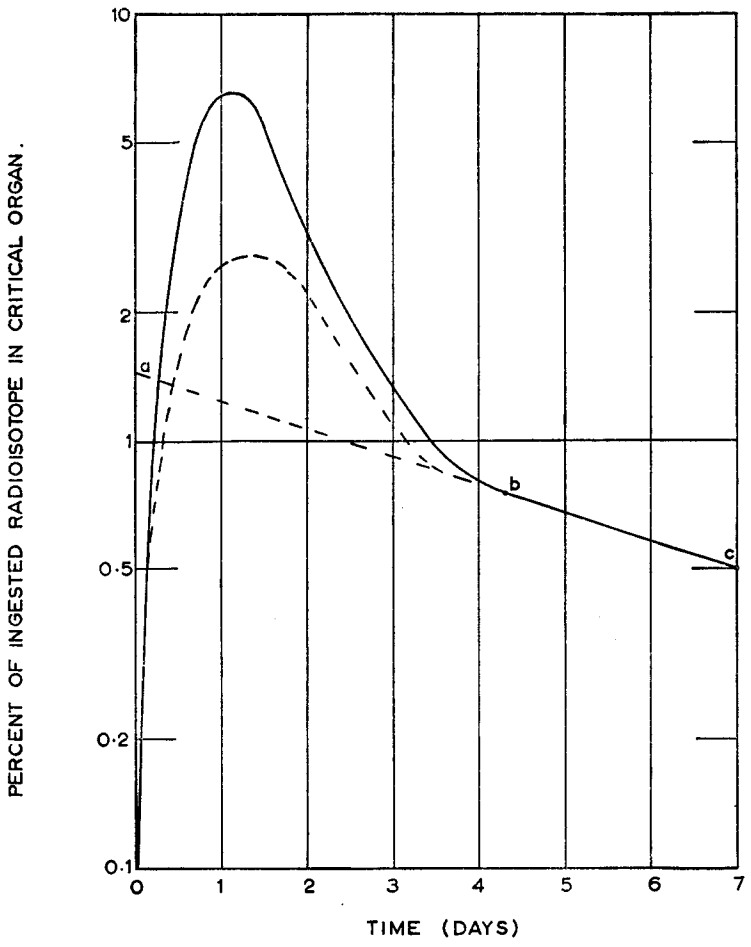

Fig. C2.

Deposition and elimination of a radioisotope in a critical body organ. Following a single ingestion.

moderately satisfactory in most cases, especially when the initial quantity of the radioisotope administered is low enough, so that (1) the metabolism resembles that which would result from a maximum permissible continuous exposure in the animal diet, (2) it does not deliver a damaging radiation dose, and (3) provided the animal observations are extended over a sufficiently long period of time so that the slope of the straight portion of curve b to c can be measured accurately. If the data given in Fig. C2 are not corrected for radioactive decay, the effective half-life is related to the ordinates of the curve at b and c by the simple relation,

$$T = \frac{0{\cdot}693t}{\log_e(b/c)} \qquad \text{.....(C3)}$$

in which t is the time interval between b and c.

It sometimes happens that data such as that indicated in Figs. C1 and C2 are not available. In this case it may be possible to assume the existence of an equilibrium condition of the body with respect to the stable form of the radioelement concerned, *i.e.* set the grammes deposited in the critical organ per day equal to the grammes eliminated per day. In this case it follows that,

$$T_b = \frac{0{\cdot}693\, m\, C}{I f_w} \qquad \text{.....(C4)}$$

Values of mass, m, of the critical organ are given in Table C.II, and values of concentration in the organ, C, normal daily intake, I, and fraction retained by ingestion, f_w, and by inhalation, f_a, are given in Table C.IV.

As seen from Fig. C2, the fraction initially retained in the critical body organ for ingestion, f_w, or for inhalation, f_a, is found by an extrapolation of line cb to the intercept, a. This intercept has no true physical significance and is the fraction of the radioisotope that would have been retained in the critical organ at time zero if the initial body distribution processes had taken place instantaneously and the decay continued from a to b to c. The initial body distribution processes may lead to a sharp maximum—solid curve—or to a broad maximum—dotted curve—in the concentration of the radioisotope in the critical body organ. So long as the area under the experimental curve is a close approximation to the area under curve abc, this method of finding the initial retention and biological half-life in the critical organ gives the desired results since this area is proportional to the total dose of ionizing radiation delivered to the critical body organ. Table C.V lists values of the effective half-life in the critical body organ for the various radioisotopes.

VI. PRODUCT OF EFFECTIVE ENERGY, RELATIVE BIOLOGICAL EFFECTIVENESS AND NON-UNIFORM DISTRIBUTION FACTOR

This is the product of (1) the effective energy in MeV delivered to the critical organ per disintegration of the radioisotope, (2) the relative biological effectiveness, (RBE), of the radiation relative to 200 kV X-radiation, and (3) a non-uniform distribution factor N. It is given by the equation,

$$\Sigma E(\mathrm{RBE})N = \sum_{i,j,K,m,n}\left[f_{\gamma_i} E_{\gamma_i}\left(1-e^{-\sigma_i X}\right) + 0{\cdot}33 f_{\beta_j} E_{\beta_j}\left(1-\frac{Z^{1/2}}{43}\right)\left(1+\frac{E_{\beta_j}^{1/2}}{4}\right)\right]\left[N_{\beta_j}\right]$$

$$10 f_{\alpha_K} E_{\alpha_K} N_{\alpha_K} + f_{e^-_m} E_{e^-_m} N_{e^-_m} + 20 f_{r_n} E_{r_n} N_{r_n} \Big] \quad \ldots\ldots\ldots\ldots\ldots\ldots (C_5)$$

in which E=effective energy in MeV.

(RBE) = relative biological effectiveness of the radiation. It is taken as 1 for β-, γ-, X-radiation, and conversion electrons, 10 for α-radiation and 20 for atom recoils.

N = non-uniform distribution factor which is assumed to be 1 for X- and γ-radiation and 5 for the $\alpha, \beta^-, \beta^+, e^-$, and atom recoil components of energy from radioisotopes deposited in the bone, with the exception of ^{226}Ra and ^{32}P. It is taken as 1 for all body organs except bone.

f_{γ_i} = fraction of the disintegrations of the i^{th} type that result in the emission of a γ or X photon of energy E_{γ_i}.

f_{β_j} = fraction of the disintegrations of the j^{th} type that result in the emission of a β ray of maximum energy E_{β_j}.

f_{α_K} = fraction of the disintegrations of the K^{th} type that result in the emission of an α ray of energy E_{α_K}.

$f_{e^-_m}$ = fraction of disintegrations of m^{th} type that result in the emission of a conversion electron of energy $E_{e^-_m}$.

f_{r_n} = fraction of disintegrations of n^{th} type that result in an atomic recoil of appreciable energy E_{r_n}. In practice $f_{r_n} = f_{\alpha_K}$.

σ_i = total coefficient of absorption minus Compton scattering coefficient in cm^{-1} of tissue for photons of energy E_{α_i}.

X = effective radius (in cm) of the critical body organ containing the radioisotope. Values of X are given in Table C.II.

Z = atomic number of the radioisotope emitting the β ray.

Table C.V lists values of the product of $\Sigma E(\text{RBE})N$ for the critical body organ selected for each radioisotope, for the G.I. tract and for the lungs. The value of $\Sigma E(\text{RBE})N$ in the case of a radioisotope with a radioactive daughter is found by properly weighting the contribution of the daughter before adding to the $\Sigma E(\text{RBE})N$ of the parent. In cases where the ratio $\frac{T_b}{T_r}$ is small for a daughter product, the weighting factor is small.

VII. UNITS OF DOSE OF IONIZING RADIATION

In this report the unit of absorbed dose of ionizing radiation called the rad is used. The rad corresponds to an energy absorption of ionizing radiation in the medium of 100 ergs per g, and the medium referred to here is human tissue at the point in question. Another unit of absorbed dose used in this report is the rem. This unit corresponds to that absorbed dose in tissue that is considered to result in biological damage equivalent to that produced by one rad of X radiation (of about 200 kV). (See report of Sub-Committee I.)

TABLE C.V

RADIOISOTOPE DATA

1	2	3	4	5	6	7
Z	Radio-isotope	Radioactive half-life (days)	Critical organ	Product of effective energy, R.B.E. and N, *i.e.* $\Sigma E(\mathrm{RBE})N$* (MeV)	Effective half-life (days)	Reference used in obtaining the critical organ**
1	^{3}H	$4{\cdot}6 \times 10^{3}$	Total body	0·006 (0·006, 0·006)	19	Hw-1, Ch-1
4	^{7}Be	54·5	Bone	0·009 (0·009, 0·037)	48	Ha-23, Ur-2
6	$^{14}C(CO_2)$	$2{\cdot}09 \times 10^{6}$	Fat	0·053 (0·053, 0·053)	35	Ss-1, Ev-1
9	^{18}F	0·078	Bone	1·2 (0·24, 0·24)	0·078	Wa-1, Gl-1
11	^{24}Na	0·62	Total body	2·7 (1·05, 2·7)	0·60	Be-1, Bl-1
15	^{32}P	14·3	Bone	0·68 (0·68, 0·68)	14	At-1, Ka-1
16	^{35}S	87·1	Skin	0·055 (0·055, 0·055)	18	Dd-1, Mn-1
17	^{36}Cl	$1{\cdot}6 \times 10^{5}$	Total body	0·26 (0·26, 0·26)	19	Sh-1, H-8
18	^{41}A	0·074	Total body	1·8		La-6
19	^{42}K	0·52	Muscle	1·6 (1·4, 1·6)	0·51	Nt-1, Gr-4
20	^{45}Ca	152	Bone	0·43 (0·085, 0·085)	151	Gr-2, No-1
21	^{46}Sc	85	Spleen Liver	0·5 0·5 (0·41, 1·3)	13 13	So-6 So-1, So-10
21	^{47}Sc	3·43	Spleen Liver	0·21 0·21 (0·21, 0·21)	2·8 2·8	So-6 So-1, So-10
21	^{48}Sc	1·83	Spleen Liver	0·65 0·80 (0·54, 1·6)	1·6 1·6	So-6 So-1, So-10
23	^{48}V	16	Bone	1·1 (0·54, 1·8)	12	Ha-16, So-9
24	^{51}Cr	26·5	Kidneys	0·007 (0·007, 0·011)	22	So-1
25	^{56}Mn	0·108	Kidneys Liver	1·1 1·1 (1·1, 1·8)	0·104 0·106	So-1 Gr-3, Co-1
26	^{55}Fe	$1{\cdot}06 \times 10^{3}$	Blood	0·006 (0·006, 0·006)	61	Ev-1, Gr-5

TABLE C.V (*continued*)

RADIOISOTOPE DATA

1	2	3	4	5	6	7
Z	Radio-isotope	Radioactive half-life (days)	Critical organ	Product of effective energy, R.B.E. and N, *i.e.* $\Sigma E(\mathrm{RBE})N$* (MeV)	Effective half-life (days)	Reference used in obtaining the critical organ**
26	^{59}Fe	46·3	Blood	0·54 (0·28, 0·81)	27	Ev-1, Gr-5
27	^{60}Co	$1·9 \times 10^{3}$	Liver	0·72 (0·43, 1·5)	8·4	Co-1, Ma-2
28	^{59}Ni	$9·1 \times 10^{7}$	Liver	0·05 (0·05, 0·05)	8	H-8
29	^{64}Cu	0·54	Liver	0·15 (0·13, 0·21)	0·53	Co-6, Be-1
30	^{65}Zn	250	Bone	0·097 (0·085, 0·33)	21	Sn-2, He-1
31	^{72}Ga	0·59	Bone	2·6 (0·8, 2·0)	0·59	Du-1, Pk-1
32	^{71}Ge	11·4	Kidneys	0·01 (0·01, 0·01)	3·9	Ha-21
33	^{76}As	1·12	Kidneys	1·1 (1·1, 1·3)	1·09	Ht-1, Ha-17
37	^{86}Rb	19·5	Muscle	0·73 (0·63, 0·73)	7·8	Ha-21
38	^{89}Sr	53	Bone	2·8 (0·55, 0·55)	52	Ha-1, Su-1
38	^{90}Sr + ^{90}Y	$9·1 \times 10^{3}$	Bone	5·1 (0·36, 0·96)	$2·7 \times 10^{3}$	Ha-1, Su-1
39	^{91}Y	57	Bone	2·8 (0·57, 0·57)	51	Se-3, Ha-7
40	^{95}Zr + ^{95}Nb	65	Bone	0·98 (0·24, 0·95)	48 21	Ha-16, Ha-7
41	^{95}Nb	35	Bone	0·33 (0·15, 0·51)	21	Ha-1, Ha-10
42	^{99}Mo	2·85	Bone	0·69 (0·22, 0·52)	2·8	Co-3, Ne-1
43	^{96}Tc	4·3	Kidneys	0·49 (0·37, 1·5)	2·1	Ha-21
44	^{106}Ru+^{106}Rh	365	Kidneys	1·4 (1·4, 1·5)	19	Ha-9, So-8
45	^{105}Rh	1·52	Kidneys	0·33 (0·30, 0·47)	1·5	So-8, So-11
46	^{103}Pd+^{103}Rh$^{(s)}$	17	Kidneys	0·074 (0·040, 0·074)	4·4	So-8

TABLE C.V (*continued*)

RADIOISOTOPE DATA

1	2	3	4	5	6	7
Z	Radio-isotope	Radioactive half-life (days)	Critical organ	Product of effective energy, R.B.E. and N, *i.e.* $\Sigma E(\mathrm{RBE})N$* (MeV)	Effective half-life (days)	Reference used in obtaining the critical organ**
47	^{105}Ag	45	Liver	0·74 (0·41, 1·7)	2·8	So-7
47	^{111}Ag	7·5	Liver	0·37 (0·37, 0·37)	2·1	So-7
48	^{109}Cd+^{109}Ag (s)	330	Liver	0·04 (0·03, 0·07)	77	Ha-21
50	^{113}Sn	112	Bone	0·087 (0·087, 0·31)	44	Ha-18, Ha-20
52	^{127}Te	90·4	Kidneys	0·28 (0·28, 0·32)	13	Ja-2, De-1
52	^{129}Te	32	Kidneys	0·89 (0·83, 1·4)	10	Ja-2, De-1
53	^{131}I	8	Thyroid	0·22 (0·24, 0·43)	7·5	La-1, Ha-1
54	^{133}Xe	5·27	Total body	0·18		La-6
54	^{135}Xe	0·38	Total body	0·56		La-6
55	^{137}Cs+^{137}Ba (s)	1·2 × 10^4	Muscle	0·57 (0·27, 0·57)	17	Ha-1, Co-7
56	^{140}Ba+^{140}La	12·8	Bone	4·1 (0·55, 1·9)	12	Do-1, Ha-1
57	^{140}La	1·67	Bone	2·9 (0·76, 1·5)	1·6	Ha-1, Ha-10
58	^{144}Ce+^{144}Pr	275	Bone	6·3 (1·29, 1·4)	180	At-2, Ha-10
59	^{143}Pr	13·8	Bone	1·6 (0·31, 0·31)	11	Ha-15, Ha-16
61	^{147}Pm	1·46 × 10^3	Bone	0·34 (0·067, 0·067)	140	Ha-1, Ha-24
62	^{151}Sm	3·6 × 10^5	Bone	0·10 (0·02, 0·02)	3·9 × 10^4	Ha-18
63	^{154}Eu	1·97 × 10^3	Bone	1·2 (0·35, 0·83)	8·2 × 10^2	Ha-15, Ha-17
67	^{166}Ho	1·14	Bone	3·2 (0·65, 0·68)	1·1	So-3
69	^{170}Tm	129	Bone	1·6 (0·32, 0·32)	59	So-6
71	^{177}Lu	6·7	Bone	0·65 (0·14, 0·17)	3·2	So-3

TABLE C.V (*continued*)

RADIOISOTOPE DATA

1	2	3	4	5	6	7
Z	Radio-isotope	Radioactive half-life (days)	Critical organ	Product of effective energy, R.B.E. and N, *i.e.* $\Sigma E(\mathrm{RBE})N$* (MeV)	Effective half-life (days)	Reference used in obtaining the critical organ**
73	^{182}Ta	111	Liver	0·44 (0·31, 0·81)	60	So-6, Su-3
74	^{181}W	140	Bone	0·37 (0·26, 1·08)	4·8	So-10
75	^{183}Re	240	Thyroid Skin	0·09 0·003 (0·15, 0·63)	0·5 5	So-2, Bu-1 So-2, So-8
77	^{190}Ir	10·7	Kidneys Spleen	0·07 0·07 (0·06, 0·20)	7·3 10	So-8 So-11
77	^{192}Ir	70	Kidneys Spleen	0·46 0·46 (0·39, 0·97)	17 45	So-8 So-11
78	^{191}Pt	3	Kidneys	0·39 (0·28, 1·22)	2·9	So-11
78	^{193}Pt	4·3	Kidneys	0·35 (0·22, 1·0)	4·0	So-11
79	^{196}Au	5·55	Liver Kidneys	0·17 0·13 (0·09, 0·38)	5 5	So-10 He-1, El-1
79	^{198}Au	2·69	Liver Kidneys	0·43 0·40 (0·38, 0·57)	2·6 2·6	So-10 He-1, El-1
79	^{199}Au	3·3	Liver Kidneys	0·16 0·14 (0·12, 0·22)	3·1 3·1	So-10 He-1, El-1
81	^{200}Tl	1·13	Muscle	1·24 (0·36, 1·24)	1·06	Bc-1, So-10
81	^{201}Tl	3	Muscle	0·16 (0·038, 0·16)	2·6	Bc-1, So-10
81	^{202}Tl	11·5	Muscle	0·21 (0·059, 0·21)	6·9	Bc-1, So-10
81	^{204}Tl	$9·9 \times 10^2$	Muscle	0·25 (0·25, 0·25)	16·7	Bc-1, So-10
82	^{203}Pb	2·17	Bone	0·12 (0·12, 0·50)	2·16	So-8, Ev-1
82	^{210}Pb + dr.	$9·1 \times 10^3$	Bone	103 (0·067, 12)	$6·76 \times 10^2$	So-8, Ev-1
84	^{210}Po	138·3	Spleen Lungs	55 56 (55, 56)	40 31	Fi-3, Fi-2 Fi-4, Fi-3

TABLE C.V (*continued*)

RADIOISOTOPE DATA

1	2	3	4	5	6	7
Z	Radio-isotope	Radioactive half-life (days)	Critical organ	Product of effective energy, R.B.E. and N, *i.e.* $\Sigma E(\mathrm{RBE})N$* (MeV)	Effective half-life (days)	Reference used in obtaining the critical organ**
85	^{211}At	0·31	Thyroid	71 (71, 71)	0·31	Ha-25, So-1
86	^{220}Rn + dr.	$6{\cdot}3 \times 10^{-4}$	Lungs	219		Bw-1
86	^{222}Rn + dr.	3·83	Body Lungs	200 200		La-6, Lr-1 Bw-1
88	^{226}Ra + 55% dr.	$5{\cdot}9 \times 10^{5}$	Bone	162 (80, 245)	$1{\cdot}6 \times 10^{4}$	Fi-3, No-1
89	^{227}Ac + dr.	8×10^{3}	Bone	1690 (2·5, 271)	10^{3}	Ha-1, Ha-16
90	Th-natural	5×10^{12}	Bone	1866 (135, 365)	$4{\cdot}3 \times 10^{4}$	Mt-1, Ha-1
90	^{234}Th + ^{234}Pa	24·1	Bone	4·3 (0·87, 0·89)	24·1	Mt-1, Ha-1
92	U-natural (sol)	$1{\cdot}64 \times 10^{12}$	Kidneys	94 (94, 94)	30	Vo-1, Ho-2
92	U-natural (insol)	$1{\cdot}64 \times 10^{12}$	Lungs	94 (94, 94)	120	Ho-3
92	^{233}U (sol)	$5{\cdot}9 \times 10^{7}$	Bone	250 (50, 50)	300	Vo-1, Ha-1
92	^{233}U (insol)	$5{\cdot}9 \times 10^{7}$	Lungs	50 (50, 50)	120	Ho-3
94	^{239}Pu (sol)	$8{\cdot}8 \times 10^{6}$	Bone	267 (53, 54)	$4{\cdot}3 \times 10^{4}$	Fi-3, Mi-1
94	^{239}Pu (insol)	$8{\cdot}8 \times 10^{6}$	Lungs	54 (53, 54)	360	Ab-1
95	^{241}Am	$1{\cdot}79 \times 10^{5}$	Bone	282 (56, 56)	890	Ha-13, Ha-10
96	^{242}Cm	150	Bone	314 (63, 63)	120	So-5, Ha-1

* The first value of $\Sigma E(\mathrm{RBE})N$ given in parenthesis applies to the radioisotope when it is contained in the critical portion of the gastrointestinal tract; the second value in parenthesis applies to the radioisotope when contained in the lungs. All other values in columns 5 and 6 apply to the critical organs listed in column 4. In the case of α-emitting radioisotopes, the energy of the recoil atoms has been included. This energy was found by using the expression, $E_{\mathrm{recoil}} = E_{\alpha}\, M_{\alpha}/M_{\mathrm{recoil}}$, and by applying an R.B.E. of 20 to recoil atoms of mass greater than 4.

** In order to condense the bibliography in this report, only one or two references are given for each element. However, it is suggested that the reader refers to the more complete bibliography in *National Bureau of Standards Handbook 52* on "Maximum Permissible Amounts of Radioisotopes in the Human Body and Maximum Permissible Concentrations in Air and Water", issued March 20, 1953, for additional references used in choosing the critical organ.

VIII. MAXIMUM PERMISSIBLE BODY BURDEN

1. *Based on a comparison with radium*

In the case of α-emitting radioisotopes that localise in the bone the maximum permissible body burden, q, is determined from a direct comparison with radium. Man has had years of experience with radium, and it is believed that the long established maximum permissible burden for radium of 0·1 μc should serve as the basis of choice of the maximum permissible body burden of other similar α-emitting radioisotopes that are deposited in the bone. It is known that radium is unevenly distributed in the bone, but evidence seems to indicate that other α-emitting radioisotopes may be even less uniformly distributed in the bone. Therefore, for the purpose of calculation the factor of non-uniform distribution, N, is taken as 1 for radium and 5 for all other α-emitting radioisotopes that are bone seekers. It follows that the maximum permissible body burden of these radioisotopes is given by the equation,

$$q = \frac{0{\cdot}1\ (0{\cdot}99)}{f_2} \times \frac{162}{\Sigma E(\mathrm{RBE})\mathcal{N}} = \frac{16}{f_2 \Sigma E(\mathrm{RBE})\mathcal{N}} \qquad \text{(C6)}$$

in which it is assumed 99 per cent of the radium in the body is in the skeleton and the total energy per disintegration of ^{226}Ra + 55 per cent of its daughter products (with proper correction for the biological elimination of Ra *D*) weighted by the R.B.E. is 162 MeV. The weighted energy is found from $\Sigma E(\mathrm{RBE})\mathcal{N}$ for other radioisotopes.

2. *Based on a permissible dose-rate to the critical body organ*

The other values of maximum permissible body burden and maximum permissible concentration in air and water, given in Table C.VIII, are developed on the premise that the maximum permissible concentration in air or water is that which will permit the accumulation of a burden of the radioisotope in the critical body organ, so that it will receive an average dose-rate of 0·3 rem/week after the contaminated air or water has been used exclusively for a time that is much longer than the effective half-life of the radioisotope in the critical body organ, but not greater than 70 years in any case. These values apply only to peace-time occupational exposures, and a factor of safety of 10 is recommended for prolonged exposure of a large population. Therefore, it follows from the above assumptions that the maximum permissible body burden, q, (μc) is given by the equation,

$$q = \frac{100\, mW}{3{\cdot}7 \times 10^4 \times 1{\cdot}6 \times 10^{-6} \times 6{\cdot}05 \times 10^5 f_2 \Sigma E(\mathrm{RBE})\mathcal{N}}$$

$$q = \frac{2{\cdot}8 \times 10^{-3}\, mW}{f_2\, \Sigma E(\mathrm{RBE})\mathcal{N}} = \frac{8{\cdot}4 \times 10^{-4} m}{f_2 \Sigma E(\mathrm{RBE})\mathcal{N}} \qquad \text{(C7)}$$

in which $3{\cdot}7 \times 10^4$ = dis/sec/μc

$1{\cdot}6 \times 10^{-6}$ = ergs/MeV

$6{\cdot}05 \times 10^5$ = sec/week

100 = ergs/g/rad

W = 0·3 rem/week

m = mass of critical organ (g)

f_2 = fraction in critical organ of total in body

$\Sigma E(\mathrm{RBE})\mathcal{N}$ = weighted energy absorption term given by equation C5

IX. MAXIMUM PERMISSIBLE CONCENTRATION (MPC) IN AIR AND WATER

1. *Maximum permissible concentration that will result in a maximum permissible body burden after a long period of exposure*

The maximum permissible concentration is found by integrating from time O to t the equation,

$$\frac{d(qf_2)}{dt} + \lambda qf_2 = P \quad \ldots\ldots\ldots\

$\frac{1}{2}$ the solid angle. Integrating W in equation C7 from the time of arrival, h_o, to the time of departure, h_1, and placing the weekly dose equal to 0·3 rem,

$$0{\cdot}3 = 7\int_{h_o}^{h_1} \frac{W}{7}\,dt = \frac{I_o\,\Sigma E(\mathrm{RBE})\,H}{2{\cdot}8 \times 10^{-3}\,m'\,G} \qquad \text{.....(C12)}$$

in which

$$G = \frac{0{\cdot}693\,H}{(e^{-0{\cdot}693h_o/T_r} - e^{-0{\cdot}693h_1/T_r})\,T_r} \qquad \text{.....(C13)}$$

and is equal to 1 for large value of T_r.

Substituting equation C12 in C11,

$$(\mathrm{MPC})_w^{\mathrm{GI}} = \frac{7{\cdot}6 \times 10^{-7}\,m'\,G}{H f_w \Sigma E(\mathrm{RBE})} \qquad \text{.....(C14)}$$

and similarly,

$$(\mathrm{MPC})_a^{\mathrm{GI}} = \frac{8{\cdot}4 \times 10^{-11}\,m'\,G}{H f_a\,\Sigma E(\mathrm{RBE})} \qquad \text{.....(C15)}$$

in which $(\mathrm{MPC})_w^{\mathrm{GI}}$ and $(\mathrm{MPC})_a^{\mathrm{GI}}$ = maximum permissible concentration (μc/c.c.) in water and air, respectively, that will deliver a dose of 0·3 rem to the critical tissue of the gastrointestinal tract in one week.

m' = mass of contents of the gastrointestinal tract in the section considered.

H = time (fraction of day) the radioactive material remains in the G.I. section considered ($H = h_1 - h_o$).

f_w and f_a = fraction of radioactive material arriving at G.I. section considered [$f_w = (1 - f_1)$ and $f_a = 0{\cdot}62(1 - f_1)$].

h_o = time of arrival in section considered following inhalation or ingestion.

h_1 = time of elimination from section following inhalation or ingestion.

Table C.VI below indicates the portion of the gastrointestinal tract that becomes the critical tissue for radioisotopes of various radioactive half-lives, and values are listed for some of the terms used in the above equations. It should be observed that $G = 1$ for large values of T_r and that the lower large intestine is the critical tissue for all the radioisotopes considered in Table C.VIII in which a portion of the gastrointestinal tract is the critical tissue with the exception of ^{56}Mn in which the upper large intestine is the critical tissue. When a portion of the gastrointestinal tract is the critical tissue and the concentration of the radioisotope in air or water is such as to result in a dose-rate of 0·3 rem/week to this tissue, the total body burden does not relate directly to the radioactive contents of the gastrointestinal tract because the irradiation of this tissue ceases a few days after the body intake of the radioisotope is discontinued. If exposure of the gastrointestinal tract to the contaminated water or air is continued over a long period of time at concentrations $(\mathrm{MPC})_w^{\mathrm{GI}}$ or $(\mathrm{MPC})_a^{\mathrm{GI}}$, arrived at by equations C14 and C15, and listed in columns 5 and 6 of Table C.VIII, the body will build up an

equilibrium body burden which is $(MPC)_w^{GI}/(MPC)_w$ or $(MPC)_a^{GI}/(MPC)_a$ of the maximum permissible body burden. These fractions of the maximum permissible body burden are listed in parentheses in column 4 of Table C.VIII. Values of $(MPC)_w^{GI}$ and $(MPC)_a^{GI}$ are given for each of the radioisotopes listed in Table C.VIII, even though they may be larger than the $(MPC)_w$ and $(MPC)_a$ values obtained for some other body organs, because, as indicated in Section X, exposure to the gastrointestinal tract may be the limiting factor when the water or air contains a mixture of radioisotopes. This results from the fact that the gastrointestinal tract receives exposure from the ingestion or inhalation of any and all of the radioisotopes, while other organs such as the thyroid or bone only concentrate certain specific radioisotopes.

TABLE C.VI

CONSTANTS USED IN APPLYING EQUATIONS C14 AND C15 TO VARIOUS SECTIONS OF THE GASTROINTESTINAL TRACT

Portion of G.I. tract that is the critical tissue	Region of application	m' (g)	H (days)	h_0 (days)	h_1 (days)	Value of T_r for which $G = 1{\cdot}00$ to $1{\cdot}01$
Lower large intestine	When $T_r > 0{\cdot}5$ day	150	18/24	13/24	31/24	$T_r > 64$ days
Small intestine	(Need not be considered)	1100	4/24	1/24	5/24	$T_r > 8{\cdot}7$ days
Upper large intestine	When $T_r < 0{\cdot}5$ day and $> 0{\cdot}08$ day	135	8/24	5/24	13/24	$T_r > 26$ days
Stomach	When $T_r < 0{\cdot}08$ day	250	1/24	0	1/24	$T_r > 1{\cdot}5$ days

3. *Maximum permissible concentration of noble gases resulting from submersion in a large cloud of radioactive gas*

In dealing with noble gases, such as ^{41}A, ^{133}Xe and ^{135}Xe, the calculations are not based on the dose delivered by the concentration of the radioactive material inside the body, but rather on the dose the person would receive if he were surrounded by an infinite cloud of the radioactive gas. This probably is over-conservative by a factor of about 2, because it is more likely that the body would be irradiated by a cloud which approaches a 2π rather than a 4π geometry. In any case, one would expect the radiation from the cloud surrounding the body to deliver a much higher dose than that from the gas held in the lungs. It follows then that an element of tissue—such as an ear—is assumed to be irradiated from all directions by this radioactive cloud of large volume, or in other words $e^{-\mu X}$ is approximately equal to 0, where μ = coefficient of attenuation of the cloud in air (cm^{-1} of air) and X = radius of cloud (cm).

The maximum permissible concentration of a noble gas under these conditions is,

$$(MPC)'_a = \left(\frac{qf_2}{m}\right) \rho_a P_a/P_t = \frac{2{\cdot}8 \times 10^{-3} W}{\Sigma E} \rho_a P_a/P_t \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (C16)$$

$$(\mathrm{MPC})_a = \frac{9 \times 10^{-7}}{\Sigma(E)} \qquad \text{(C17)}$$

in which $\frac{qf_2}{m}$ = μc/g of tissue as given by equation C7 in which (RBE)$\mathcal{N}$ = 1

ρ_a = density of air (= 0·0012 g/c.c.),

P_a/P_t = stopping power of air relative to tissue. P_a/P_t = 1/1·13 for β and secondary electrons produced by X- and γ-radiation,

$(\mathrm{MPC})'_a$ = maximum permissible concentration in a large cloud of gas—applied here only to noble gases—that will deliver a dose at the rate of 0·3 rem/week.

X. EXPLANATION OF VALUES SELECTED FOR THE MAXIMUM PERMISSIBLE BODY BURDEN AND MAXIMUM PERMISSIBLE CONCENTRATION

1. *Summary of assumptions and values used in equations in obtaining the maximum permissible values*

In order to aid the reader in checking the maximum permissible values given in Table C.VIII and to simplify the procedure of finding values for additional radioisotopes not listed in Table C.VIII, the general assumptions of this report are summarised in Table C.VII.

In most cases, maximum permissible values are given in Table C.VIII for the gastrointestinal tract and one or two additional body organs. Values for insoluble compounds are given in only a few cases, but they can be calculated easily by the method indicated in reference (*a*) to Table C.VIII. In general the smallest values that are applicable to the particular case should be used as the maximum permissible values.

Most of the values listed in Table C.VIII were obtained by the substitution of data from Tables C.I to C.VII into equations C6, C7, C9, C10, C14, C15 and C17. Each maximum permissible value is followed in parenthesis by a number, which indicates the number of the equation used in obtaining it or by a letter which refers to other means of selecting it.

2. *References to Table C.VIII*

(a) References were considered to apply if the values agreed with the accepted value within ± 50 per cent. Calculated values were rounded off to one significant figure. The principal reference responsible for the choice of a particular value was listed first.

In order to conserve space only a few $(\mathrm{MPC})_a$ values are listed in Table C.VIII for insoluble compounds when the lung is the critical organ. Making use of the assumptions outlined in Table C.VII and combining equations C7 and C9, the general equation for $(\mathrm{MPC})_a$ of insoluble compounds when the lung is the critical tissue becomes,

$$(\mathrm{MPC})_a = 2 \times 10^{-9}/\Sigma E(\mathrm{RBE})\mathcal{N}$$

If one wishes to find $(\mathrm{MPC})_a$, appropriate values of $\Sigma E(\mathrm{RBE})\mathcal{N}$ are given as the second number in parenthesis in column 5 of Table C.V.

TABLE C.VII

A SUMMARY OF ASSUMPTIONS AND REFERENCES TO VALUES USED IN EQUATIONS IN OBTAINING THE MAXIMUM PERMISSIBLE VALUES LISTED IN TABLE C.VIII

Type of radioactive material	Type of exposure	Critical tissue	Fraction initially retained in critical organ	Weighted effective energy per disintegration $\Sigma E(\mathrm{RBE})N$	Mass of critical organ (g)	Half-life	Equation used for finding max. per. conc. (MPC)	Equation used for finding total body burden (q)
Soluble	Inhalation	Lungs	$f_a=0{\cdot}25\ (1-f_1)$	*2nd* value in parenthesis in column 5 of Table C.V	1000	T_b = 1 day	Eq. C9	Eq. C7
		Organ listed in column 4 of Table C.V and column 3 of Table C.VIII	$f_a=(0{\cdot}25+0{\cdot}5f_1)f_2$ Value listed in columns 6, 12, and 19 of Table C.IV	Value not in parenthesis in column 5 of Table C.V	Column 3 of Table C.VIII	Value of T given in column 6 of Table C.V	Eq. C9	Eq. C6 or C7
	Ingestion	Organ listed in column 4 of Table C.V and column 3 of Table C.VIII	Values of f_w given in columns 5, 11, and 18 of Table C.IV	Value not in parenthesis in column 5 of Table C.V	Column 3 of Table C.VIII	Values of T given in column 6 of Table C.V	Eq. C10	Eq. C6 or C7
Insoluble and slightly soluble	Inhalation	Lungs	$f_a = 0{\cdot}12$	*2nd* value in parenthesis in column 5 of Table C.V	1000	T_b = 120 days	Eq. C9	Eq. C7
		A portion of the GI tract	$f_a = 0{\cdot}62(1-f_1)$	1st value in parenthesis in column 5 of Table C.V	Values listed in column 3 of Table C.VI	Values of H, h_a, and h_1 listed in columns 4, 5, and 6 of Table C.VI	Eq. C15	Ratio
	Ingestion	A portion of the GI tract	$f_w = (1-f_1)$	1st value in parenthesis in column 5 of Table C.V	Values listed in column 3 of Table C.VI	Values of H, h_a, and h_1 listed in columns 4, 5 and 6 of Table C.VI	Eq. C14	Ratio
Noble gas	External (submersion)	Total body		Column 5 of Table C.V	70,000	Values of T_r given in column 3 of Table C.V	Eq. C17	

TABLE C.VIII

MAXIMUM PERMISSIBLE AMOUNT OF RADIOISOTOPE IN TOTAL BODY AND MAXIMUM PERMISSIBLE CONCENTRATION IN AIR AND WATER FOR CONTINUOUS EXPOSURE[a]

Z	Radioisotope and type of decay	Critical organ (g)	Maximum permissible[m] total body burden, q (μc)	Maximum permissible concentrations In water (μc/c.c.)	In air (μc/c.c.)
1	^{3}H (HTO or $^{3}H_2O$) β^-	Total body 7×10^4 (GI) 150	10^4 (Eq. C7, c) (10^4, 10^4)	0·2 (Eq. C10) 0·2 (Eq. C14)	10^{-5} (Eq. C9, d, g) 10^{-5} (Eq. C15)
4	^{7}Be K, γ	Bone 7×10^3 (GI) 150	725 (Eq. C7) (15, 440)	1 (Eq. C10) 2×10^{-2} (Eq. C14)	5×10^{-6} (Eq. C9) 3×10^{-6} (Eq. C15)
6	$^{14}C(CO_2)$ β^-	Fat 10^4 (GI) 150	260 (Eq. C7) (5×10^3, 260)	3×10^{-3} (Eq. C10) 6×10^{-3} (Eq. C14)	10^{-5} (d) 10^{-5} (Eq. C15)
9	^{18}F β^+	Bone 7×10^3 (GI) 150	5 (Eq. C7) (> 5)	0·2 (Eq. C10) $>0·2$ (Eq. C14)	3×10^{-5} (Eq. C9) $>3 \times 10^{-5}$ (Eq. C15)
11	^{24}Na β^-, γ	Total body 7×10^4 (GI) 150	15 (Eq. C7, b, c) (15, 8)	8×10^{-3} (b, c) 8×10^{-3} (Eq. C14)	2×10^{-6} (Eq. C9, b) 10^{-6} (Eq. C15)
15	^{32}P β^-	Bone 7×10^3 (GI) 150	10 (b, c) (40, 10)	2×10^{-4} (b, c) 8×10^{-4} (Eq. C14)	10^{-7} (Eq. C9) 10^{-7} (Eq. C15)
16	^{35}S β^-	Skin 2×10^3 (GI) 150	300 (Eq. C7) (360, 300)	5×10^{-3} (Eq. C10) 6×10^{-3} (Eq. C14)	10^{-6} (Eq. C9, b) 10^{-6} (Eq. C15)
17	^{36}Cl β^-	Total body 7×10^4 (GI) 150	230 (Eq. C7) (580, 770)	4×10^{-3} (Eq. C10) 10^{-2} (Eq. C14)	6×10^{-7} (Eq. C9) 2×10^{-6} (Eq. C15)
18	^{41}A β^-	Total body 7×10^4	33 (Eq. C7)	5×10^{-4} (Eq. C16)	5×10^{-7} (Eq. C17)
19	^{42}K β^-, γ	Muscle 3×10^4 (GI) 150	21 (Eq. C7) (6, 6)	10^{-2} (Eq. C10) 3×10^{-3} (Eq. C14)	2×10^{-6} (Eq. C9) 6×10^{-7} (Eq. C15)
20	^{45}Ca β^-	Bone 7×10^3 (GI) 150	14 (Eq. C7) (3×10^3, 5×10^3)	10^{-4} (Eq. C10) 2×10^{-2} (Eq. C14)	8×10^{-9} (Eq. C9) 3×10^{-6} (Eq. C15)
21	^{46}Sc β^-, γ	Spleen 150 Liver $1·7 \times 10^3$ (GI) 150	6 (Eq. C7) 5 (Eq. C7) (6×10^{-3}, 7)	0·4 (Eq. C10) 0·3 (Eq. C10) 4×10^{-4} (Eq. C14)	7×10^{-8} (Eq. C9) 5×10^{-8} (Eq. C9) 7×10^{-8} (Eq. C15)
21	^{47}Sc β^-	Spleen 150 Liver $1·7 \times 10^3$ (GI) 150	15 (Eq. C7) 11 (Eq. C7) (3×10^{-3}, 3)	4 (Eq. C10) 3 (Eq. C10) 9×10^{-4} (Eq. C14)	9×10^{-7} (Eq. C9) 6×10^{-7} (Eq. C9) 2×10^{-7} (Eq. C15)
21	^{48}Sc β^-, γ	Spleen 150 Liver $1·7 \times 10^3$ (GI) 150	5 (Eq. C7) 3 (Eq. C7) (7×10^{-4}, 0·6)	3 (Eq. C10) 1 (Eq. C10) 4×10^{-4} (Eq. C14)	6×10^{-7} (Eq. C9) 3×10^{-7} (Eq. C9) 7×10^{-8} (Eq. C15)
23	^{48}V K, β^+, γ	Bone 7×10^3 (GI) 150	10 (Eq. C7) (0·01, 0·8)	0·3 (Eq. C10) 3×10^{-4} (Eq. C14)	6×10^{-7} (Eq. C9) 5×10^{-8} (Eq. C15)
[illegible]	[illegible]	[illegible] (GI) 150	[illegible] (Eq. C7) (17, 240)	0·7 (Eq. C10) 2×10^{-2} (Eq. C14)	10^{-5} (Eq. C9) 4×10^{-6} (Eq. C15)
25	^{56}Mn β^-, γ	Kidneys 300 Liver [illegible]	25 (Eq. C7)	0·15 (Eq. C10)	[illegible] (Eq. C9)

23	^{48}V	K, β^+, γ	Bone (GI)	7×10^3 150	10 (0·01, 0·8)	(Eq. C7)	0·3 3×10^{-4}	(Eq. C10) (Eq. C14)	6×10^{-7} 5×10^{-8}	(Eq. C9) (Eq. C15)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
25	^{56}Mn	β^-, γ	Kidneys Liver (GI)	300 $1·7 \times 10^3$ 135	25 8 (0·4, 3)	(Eq. C7) (Eq. C7)	0·15 0·4 3×10^{-3}	(Eq. C10) (Eq. C10) (Eq. C14)	4×10^{-6} 4×10^{-6} 5×10^{-7}	(Eq. C9) (Eq. C9) (Eq. C15)
26	^{55}Fe	K	Blood (GI)	$5·4 \times 10^3$ 150	10^3 $(2 \times 10^4, 3 \times 10^4)$	(Eq. C7)	5×10^{-3} 0·1	(Eq. C10) (Eq. C14)	7×10^{-7} 2×10^{-5}	(Eq. C9) (Eq. C15)
26	^{59}Fe	β^-, γ	Blood (GI)	$5·4 \times 10^3$ 150	13 (390, 320)	(Eq. C7)	10^{-4} 3×10^{-3}	(Eq. C10) (Eq. C14)	2×10^{-8} 5×10^{-7}	(Eq. C9) (Eq. C15)
27	^{60}Co	β^-, γ	Liver (GI)	$1·7 \times 10^3$ 150	3 (0·06, 0·2)	(Eq. C7)	2×10^{-2} 4×10^{-4}	(Eq. C10) (Eq. C14)	10^{-6} 8×10^{-8}	(Eq. C9) (Eq. C15)
28	^{59}Ni	K	Liver (GI)	$1·7 \times 10^3$ 150	42 (0·6, 1)	(Eq. C7)	0·3 4×10^{-3}	(Eq. C10) (Eq. C14)	2×10^{-5} 7×10^{-7}	(Eq. C9) (Eq. C15)
29	^{64}Cu	K, β^- β^+, γ	Liver (GI)	$1·7 \times 10^3$ 150	120 (10, 22)	(Eq. C7)	6×10^{-2} 5×10^{-3}	(Eq. C10) (Eq. C14)	5×10^{-6} 9×10^{-7}	(Eq. C9) (Eq. C15)
30	^{65}Zn	K, β^+, γ	Bone (GI)	7×10^3 150	400 (13, 80)	(Eq. C7)	6×10^{-2} 2×10^{-3}	(Eq. C10) (Eq. C14)	2×10^{-6} 4×10^{-7}	(Eq. C9) (Eq. C15)
31	^{72}Ga	β^-, γ	Bone (GI)	7×10^3 150	3 $(5 \times 10^{-4}, 0·3)$	(Eq. C7)	3 5×10^{-4}	(Eq. C10) (Eq. C14)	10^{-6} 10^{-7}	(Eq. C9) (Eq. C15)
32	^{71}Ge	K	Kidneys (GI)	300 150	72 (0·1, 5)	(Eq. C7)	10 2×10^{-2}	(Eq. C10) (Eq. C14)	4×10^{-5} 3×10^{-6}	(Eq. C9) (Eq. C15)
33	^{76}As	β^-, γ	Kidneys (GI)	300 150	11 (0·01, 0·2)	(Eq. C7)	0·2 2×10^{-4}	(Eq. C10) (Eq. C14)	2×10^{-6} 4×10^{-8}	(Eq. C9) (Eq. C15)
37	^{86}Rb	β^-, γ	Muscle (GI)	3×10^4 150	64 (64, 64)	(Eq. C7)	3×10^{-3} 3×10^{-3}	(Eq. C10) (Eq. C14)	4×10^{-7} 4×10^{-7}	(Eq. C9) (Eq. C15)
38	^{89}Sr	β^-	Bone (GI)	7×10^3 150	2 (20, 10)	(Eq. C7, c, d)	7×10^{-5} 7×10^{-4}	(f) (Eq. C14)	2×10^{-8} 10^{-7}	(f) (Eq. C15)
38	$^{90}Sr + ^{90}Y$	β^- (h)	Bone (GI)	7×10^3 150	1 $(10^3, 10^3)$	(c, d)	8×10^{-7} 10^{-3}	(c) (Eq. C14)	2×10^{-10} 2×10^{-7}	(b, c) (Eq. C15)
39	^{91}Y	β^-	Bone (GI)	7×10^3 150	3 (0·02, 17)	(Eq. C7)	4×10^{-3} 3×10^{-4}	(Eq. C10) (Eq. C14)	9×10^{-9} 5×10^{-8}	(Eq. C9) (Eq. C15)
40	$^{95}Zr + ^{95}Nb$	β, γ	Bone (GI)	7×10^3 150	10 (0·02, 12)	(Eq. C7)	0·4 6×10^{-4}	(Eq. C10) (Eq. C14)	8×10^{-8} 10^{-7}	(Eq. C9) (Eq. C15)
41	^{95}Nb	β^-, γ	Bone (GI)	7×10^3 150	44 (44, 62)	(Eq. C7)	2×10^{-3} 2×10^{-3}	(Eq. C10) (Eq. C14)	2×10^{-7} 3×10^{-7}	(Eq. C9) (Eq. C15)
42	^{99}Mo	β^-, γ	Bone (GI)	7×10^3 150	17 (0·01, 0·01)	(Eq. C7)	5 3×10^{-3}	(Eq. C10) (Eq. C14)	6×10^{-4} 5×10^{-7}	(Eq. C9) (Eq. C15)
43	^{96}Tc	K, γ	Kidneys (GI)	300 150	5 (0·2, 0·3)	(Eq. C7)	3×10^{-2} 10^{-3}	(Eq. C10) (Eq. C14)	3×10^{-6} 2×10^{-7}	(Eq. C9) (Eq. C15)

TABLE C.VIII (*continued*)

Z	Radioisotope and type of decay	Critical organ (g)	Maximum permissible [m] total body burden, q (μc)	Maximum permissible concentration In water (μc/c.c.)	In air (μc/c.c.)
44	$^{106}Ru+^{106}Rh$ β^-, γ (h)	Kidneys 300 (GI) 150	4 (Eq. C7) (4×10^{-3}, 3)	0·1 (Eq. C10) 10^{-4} (Eq. C14)	3×10^{-8} (Eq. C9) 2×10^{-8} (Eq. C15)
45	^{105}Rh β^-, γ	Kidneys 300 (GI) 150	9 (Eq. C7) (0·02, 0·9)	0·4 (Eq. C10) 10^{-3} (Eq. C14)	2×10^{-6} (Eq. C9) 2×10^{-7} (Eq. C15)
46	$^{103}Pd+^{103}Rh^{(s)}$ K, ϵ^-(h)	Kidneys 300 (GI) 150	7 (Eq. C7) (4, 8)	10^{-2} (Eq. C10) 5×10^{-3} (Eq. C14)	8×10^{-7} (Eq. C9) 9×10^{-7} (Eq. C15)
47	^{105}Ag K, γ	Liver $1{\cdot}7 \times 10^3$ (GI) 150	19 (Eq. C7) (4×10^{-3}, 0·1)	2 (Eq. C10) 4×10^{-4} (Eq. C14)	10^{-5} (Eq. C9) 7×10^{-8} (Eq. C15)
47	^{111}Ag β^-	Liver $1{\cdot}7 \times 10^3$ (GI) 150	39 (Eq. C7) (4×10^{-3}, 0·1)	5 (Eq. C10) 5×10^{-4} (Eq. C14)	3×10^{-5} (Eq. C9) 8×10^{-8} (Eq. C15)
48	$^{109}Cd+^{109}Ag^{(s)}$ K, γ(h)	Liver $1{\cdot}7 \times 10^3$ (GI) 150	45 (Eq. C7) (450, 6×10^4)	7×10^{-2} (Eq. C10) 0·7 (Eq. C14)	7×10^{-8} (Eq. C9) 10^{-4} (Eq. C15)
50	^{113}Sn K, γ	Bone 7×10^3 (GI) 150	84 (Eq. C7) (0·8, 42)	0·2 (Eq. C10) 2×10^{-3} (Eq. C14)	6×10^{-7} (Eq. C9) 3×10^{-7} (Eq. C15)
52	^{127}Te β^-, γ	Kidneys 300 (GI) 150	4 (Eq. C7) (0·09, 4)	3×10^{-2} (Eq. C10) 7×10^{-4} (Eq. C14)	10^{-7} (Eq. C9) 10^{-7} (Eq. C15)
52	^{129}Te β^-, γ	Kidneys 300 (GI) 150	1·4 (Eq. C7) (0·03, 1·4)	10^{-2} (Eq. C10) 2×10^{-4} (Eq. C14)	4×10^{-8} (Eq. C9) 4×10^{-8} (Eq. C15)
53	^{131}I β^-, γ	Thyroid 20 (GI) 150	0·6 (Eq. C7, d) (>0·6)	6×10^{-5} (d) $>6 \times 10^{-5}$ (Eq. C14)	6×10^{-9} (d) $>6 \times 10^{-9}$ (Eq. C15)
54	^{133}Xe β^-, γ	Total body 7×10^4	320 (Eq. C7)	4×10^{-3} (Eq. C16)	4×10^{-6} (Eq. C17)
54	^{135}Xe β^-, γ	Total body 7×10^4	100 (Eq. C7)	10^{-2} (Eq. C16)	2×10^{-6} (Eq. C17, b)
55	$^{137}Cs+^{137}Ba^{(s)}$ β^-, γ(h)	Muscle 3×10^4 (GI) 150	98 (Eq. C7) (98, 98)	2×10^{-3} (Eq. C10) 2×10^{-3} (Eq. C14)	2×10^{-7} (Eq. C9) 2×10^{-7} (Eq. C15)
56	$^{140}Ba+^{140}La$ β^-, γ(h)	Bone 7×10^3 (GI) 150	1 (Eq. C7) (0·7, 3)	5×10^{-4} (Eq. C10) 3×10^{-4} (Eq. C14)	2×10^{-8} (Eq. C9) 6×10^{-8} (Eq. C15)
57	^{140}La β^-, γ	Bone 7×10^3 (GI) 150	7 (Eq. C7) (7×10^{-2}, 0·9)	0·3 (Eq. C10) 3×10^{-4} (Eq. C14)	4×10^{-7} (Eq. C9) 5×10^{-8} (Eq. C15)
58	$^{144}Ce+^{144}Pr$ β^-, γ(h)	Bone 7×10^3 (GI) 150	1 (Eq. C7) (0·01, 10)	8×10^{-3} (Eq. C10) 10^{-4} (Eq. C14)	2×10^{-9} (Eq. C9) 2×10^{-8} (Eq. C15)
59	^{143}Pr β^-	Bone 7×10^3 (GI) 150	6 (Eq. C7) (0·04, 3)	8×10^{-3} (Eq. C10) 5×10^{-4} (Eq. C14)	2×10^{-7} (Eq. C9) 9×10^{-8} (Eq. C15)
61	^{147}Pm β^-	Bone 7×10^3	25 (Eq. C7)	0·2 (Eq. C10)	4×10^{-9} (Eq. C9)
62	^{151}Sm β^-	Bone 7×10^3 (GI) 150	90 (Eq. C7) (14, 3×10^4)	5×10^{-2} (Eq. C10) 8×10^{-3} (Eq. C14)	3×10^{-9} (Eq. C9) 10^{-6} (Eq. C15)
63	^{154}Eu β^-, γ	Bone 7×10^3	7 (Eq. C7)	10^{-2} (Eq. C10)	2×10^{-9} (Eq. C9)

58	$^{144}Ce+^{144}Pr$	β^-, γ(h)	Bone (GI)	7×10^6 150	1 (0·01, 10)	(Eq. C7)	8×10^{-5} 10^{-4}	(Eq. C10) (Eq. C14)	2×10^{-7} 2×10^{-8}	(Eq. C9) (Eq. C15)
59	^{143}Pr	β^-	Bone (GI)	7×10^3 150	6 (0·04, 3)	(Eq. C7)	8×10^{-3} 5×10^{-4}	(Eq. C10) (Eq. C14)	2×10^{-7} 9×10^{-8}	(Eq. C9) (Eq. C15)
61	^{147}Pm	β^-	Bone (GI)	7×10^3 150	25 (0·2, 250)	(Eq. C7)	0·2 2×10^{-3}	(Eq. C10) (Eq. C14)	4×10^{-8} 4×10^{-7}	(Eq. C9) (Eq. C15)
62	^{151}Sm	β^-	Bone (GI)	7×10^3 150	90 (14, 3×10^4)	(Eq. C7)	3×10^{-3} 8×10^{-3}	(Eq. C10) (Eq. C14)	3×10^{-8} 10^{-6}	(Eq. C9) (Eq. C15)
63	^{154}Eu	β^-, γ	Bone (GI)	7×10^3 150	7 (0·3, 280)	(Eq. C7)	10^{-2} 4×10^{-4}	(Eq. C10) (Eq. C14)	2×10^{-9} 8×10^{-8}	(Eq. C9) (Eq. C15)
67	^{166}Ho	β^-, γ	Bone (GI)	7×10^3 150	4 (4×10^{-4}, 0·4)	(Eq. C7)	5 5×10^{-4}	(Eq. C10) (Eq. C14)	8×10^{-7} 8×10^{-8}	(Eq. C9) (Eq. C15)
69	^{170}Tm	β^-, γ	Bone (GI)	7×10^3 150	4 (0·03, 32)	(Eq. C7)	6×10^{-2} 5×10^{-4}	(Eq. C10) (Eq. C14)	10^{-8} 8×10^{-8}	(Eq. C9) (Eq. C15)
71	^{177}Lu	β^-, γ	Bone (GI)	7×10^3 150	18 (3×10^{-3}, 4)	(Eq. C7)	6 10^{-3}	(Eq. C10) (Eq. C14)	10^{-6} 2×10^{-7}	(Eq. C9) (Eq. C15)
73	^{182}Ta	β^-, γ	Liver (GI)	$1{\cdot}7 \times 10^3$ 150	6 (0·03, 27)	(Eq. C7)	10^{-1} 5×10^{-4}	(Eq. C10) (Eq. C14)	2×10^{-8} 9×10^{-8}	(Eq. C9) (Eq. C15)
74	^{181}W	K, γ, ϵ^-	Bone (GI)	7×10^3 150	24 (0·2, 0·5)	(Eq. C7)	0·1 7×10^{-4}	(Eq. C10) (Eq. C14)	5×10^{-6} 10^{-7}	(Eq. C9) (Eq. C15)
75	^{183}Re	K, γ	Thyroid Skin (GI)	20 2×10^3 150	37 650 (0·8, 2)	(Eq. C7) (Eq. C7)	9×10^{-2} 0·3 2×10^{-3}	(Eq. C10) (Eq. C10) (Eq. C14)	9×10^{-6} 3×10^{-5} 4×10^{-7}	(Eq. C9) (Eq. C9) (Eq. C15)
77	^{190}Ir	β^-, γ	Kidneys Spleen (GI)	300 150 150	23 21 (0·3, 13)	(Eq. C7) (Eq. C7)	10^{-2} 0·2 3×10^{-3}	(Eq. C10) (Eq. C10) (Eq. C14)	8×10^{-7} 10^{-6} 6×10^{-7}	(Eq. C9) (Eq. C9) (Eq. C15)
77	^{192}Ir	β^-, γ	Kidneys Spleen (GI)	300 150 150	3 3 (0·3, 5)	(Eq. C7) (Eq. C7)	9×10^{-4} 6×10^{-3} 5×10^{-4}	(Eq. C10) (Eq. C10) (Eq. C14)	5×10^{-8} 3×10^{-8} 9×10^{-8}	(Eq. C9) (Eq. C9) (Eq. C15)
78	^{191}Pt	K, γ	Kidneys (GI)	300 150	2 (0·2, 1)	(Eq. C7)	6×10^{-3} 7×10^{-4}	(Eq. C10) (Eq. C14)	2×10^{-7} 10^{-7}	(Eq. C9) (Eq. C15)
78	^{193}Pt	K, γ, ϵ^-	Kidneys (GI)	300 150	3 (0·5, 3)	(Eq. C7)	5×10^{-3} 9×10^{-4}	(Eq. C10) (Eq. C14)	2×10^{-7} 2×10^{-7}	(Eq. C9) (Eq. C15)
79	^{196}Au	K, β^-, γ	Liver Kidneys (GI)	$1{\cdot}7 \times 10^3$ 300 150	8 32 (0·3, 16)	(Eq. C7) (Eq. C7)	5×10^{-2} 5×10^{-3} 2×10^{-3}	(Eq. C10) (Eq. C10) (Eq. C14)	2×10^{-7} 2×10^{-7} 4×10^{-7}	(Eq. C9) (Eq. C9) (Eq. C15)
79	^{198}Au	β^-, γ	Liver Kidneys (GI)	$1{\cdot}7 \times 10^3$ 300 150	3 10 (0·05, 1·5)	(Eq. C7) (Eq. C7)	4×10^{-3} 3×10^{-3} 6×10^{-4}	(Eq. C10) (Eq. C10) (Eq. C14)	2×10^{-7} 10^{-7} 10^{-7}	(Eq. C9) (Eq. C9) (Eq. C15)
79	^{199}Au	β^-, γ	Liver Kidneys (GI)	$1{\cdot}7 \times 10^3$ 300 150	9 30 (0·2, 7)	(Eq. C7) (Eq. C7)	9×10^{-3} 8×10^{-3} 2×10^{-3}	(Eq. C10) (Eq. C10) (Eq. C14)	4×10^{-7} 3×10^{-7} 3×10^{-7}	(Eq. C9) (Eq. C9) (Eq. C15)
81	^{200}Tl	K, γ, ϵ^-	Muscle (GI)	3×10^4 150	40 (2, 4)	(Eq. C7) (Eq. C7)	2×10^{-2} 10^{-3}	(Eq. C10) (Eq. C14)	2×10^{-6} 2×10^{-7}	(Eq. C9) (Eq. C15)
81	^{201}Tl	K, γ	Muscle (GI)	3×10^4 150	310 (35, 89)	(Eq. C7)	8×10^{-2} 9×10^{-3}	(Eq. C10) (Eq. C14)	7×10^{-6} 2×10^{-6}	(Eq. C9) (Eq. C15)

Z	Radioisotope and type of decay		Critical organ (g)		Maximum permissible [m] total body burden, q (μc)		Maximum permissible concentration In water (μc/c.c.)		In air (μc/c.c.)	
81	^{202}Tl	K, γ, ϵ^-	Muscle (GI)	3×10^4 150	230 (58, 100)	(Eq. C7)	2×10^{-2} 5×10^{-3}	(Eq. C10) (Eq. C14)	2×10^{-6} 9×10^{-7}	(Eq. C9) (Eq. C15)
81	^{204}Tl	β^-	Muscle (GI)	3×10^4 150	200 (25, 50)	(Eq. C7)	8×10^{-3} 10^{-3}	(Eq. C10) (Eq. C14)	8×10^{-7} 2×10^{-7}	(Eq. C9) (Eq. C15)
82	^{203}Pb	K, γ	Bone (GI)	7×10^3 150	61 (1, 4)	(Eq. C7)	0·1 2×10^{-3}	(Eq. C10) (Eq. C14)	7×10^{-6} 4×10^{-7}	(Eq. C9) (Eq. C15)
82	^{210}Pb + dr	α, β^-, γ(h)	Bone (GI)	7×10^3 150	0·2 (300, 10^3)	(Eq. C6)	2×10^{-6} 3×10^{-3}	(Eq. C10) (Eq. C14)	8×10^{-11} 4×10^{-7}	(Eq. C9) (Eq. C15)
84	^{210}Po (sol)	α, γ	Spleen (GI)	150 150	0·04 (4×10^{-3}, 0·04)	(Eq. C7)	3×10^{-5} 3×10^{-6}	(Eq. C10) (Eq. C14)	5×10^{-10} 5×10^{-10}	(Eq. C9) (Eq. C15)
84	^{210}Po (insol)	α, γ	Lungs	10^3	0·02	(Eq. C7)			10^{-10}	(Eq. C9)
85	^{211}At	K, α	Thyroid (GI)	20 150	10^{-3} ($>10^{-3}$)	(Eq. C7)	3×10^{-6} $>3 \times 10^{-6}$	(Eq. C10) (Eq. C14)	5×10^{-10} $>5 \times 10^{-10}$	(Eq. C9) (Eq. C15)
86	^{220}Rn + dr	α, β, γ	Lungs	10^3					10^{-7}	(d, j)
86	^{222}Rn + dr	α, β, γ	Lungs	10^3					10^{-7}	(d, j)
88	^{226}Ra + 55% dr	α, β, γ(h)	Bone	7×10^3	0·1	(b, c, d)	4×10^{-8}	(b, c)	8×10^{-12}	(c, d)
89	^{227}Ac + dr	α, β, γ(h)	Bone (GI)	7×10^3 150	0·01 (0·02, 0·07)	(Eq. C6)	2×10^{-6} 5×10^{-7} 10^{-6}	(Eq. C10) (Eq. C14)	4×10^{-12} 3×10^{-11} 2×10^{-10}	(Eq. C9) (d) (Eq. C15)
90	Th natural	α, β, γ(t)	Bone (GI)	7×10^3 150	0·01 (0·02, 0·07)	(Eq. C6)	5×10^{-7} 10^{-6}	(Eq. C10) (Eq. C14)	3×10^{-11} 2×10^{-10}	(d) (Eq. C15)
90	Th natural	α								

88	^{226}Ra + 55% dr	α, β, γ(h)	Bone	7×10^3	0·1	(b, c, d)	4×10^{-8}	(b, c)	8×10^{-12}	(c, d)
89	^{227}Ac + dr	α, β, γ(h)	Bone (GI)	7×10^3 150	0·01 (0·2, 25)	(Eq. C6)	3×10^{-6} 6×10^{-5}	(Eq. C10) (Eq. C14)	4×10^{-12} 10^{-8}	(Eq. C9) (Eq. C15)
90	Th-natural (insol)	α, β, γ	Lungs	10^3	2×10^{-3}	(Eq. C7)			3×10^{-11}	(d)
90	^{234}Th+^{234}Pa	β^-, γ(h)	Bone (GI)	7×10^3 150	2 (8×10^{-3}, 6)	(Eq. C7)	5×10^{-2} 2×10^{-4}	(Eq. C10) (Eq. C14)	10^{-8} 3×10^{-8}	(Eq. C9) (Eq. C15)
92	U-natural (sol)	α, β^-, γ(r)	Kidneys (GI)	300 150	0·04 (8×10^{-4}, 0·4)	(Eq. C9, e)	10^{-4} 2×10^{-6}	(Eq. C10, e) (Eq. C14)	3×10^{-11} 3×10^{-10}	(d, e) (Eq. C15)
92	U-natural (insol)	α, β^-, γ	Lungs	10^3	0·01	(Eq. C7)			3×10^{-11}	(d, e)
92	^{233}U (sol)	α, γ	Bone (GI)	7×10^3 150	0·04 (8×10^{-4}, 0·07)	(c)	$1{\cdot}5 \times 10^{-4}$ 3×10^{-6}	(c) (Eq. C14)	3×10^{-11} 5×10^{-10}	(f) (Eq. C15)
92	^{233}U (insol)	α, γ	Lungs	10^3	0·016	(d)			3×10^{-11}	(d)
94	^{239}Pu (sol)	α, γ	Bone (GI)	7×10^3 150	0·04 (0·02, 10)	(c, d)	6×10^{-6} 3×10^{-6}	(Eq. C10, d) (Eq. C14)	2×10^{-12} 5×10^{-10}	(c) (Eq. C15)
94	^{239}Pu (insol)	α, γ	Lungs	10^3	0·02	(Eq. C7)			2×10^{-12}	(b, c)
95	^{241}Am	α, γ	Bone (GI)	7×10^3 150	0·06 (9×10^{-4}, 0·8)	(Eq. C6)	2×10^{-4} 3×10^{-6}	(Eq. C10) (Eq. C14)	4×10^{-11} 5×10^{-10}	(Eq. C9) (Eq. C15)
96	^{242}Cm	α	Bone (GI)	7×10^3 150	0·06 (10^{-4}, 0·1)	(Eq. C6)	10^{-3} 2×10^{-6}	(Eq. C10) (Eq. C14)	2×10^{-10} 4×10^{-10}	(Eq. C9) (Eq. C15)
Any fission mixture (β, γ)							10^{-7}		10^{-9}	
Any mixture of α emitters							10^{-7}		5×10^{-12}	

(b) Values suggested by the Chalk River, Canada, Conference, September 1949.

(c) International Recommendations on Radiological Protection, Sixth International Congress of Radiology in London, July 1950 (*British Journal of Radiology*, July 1951), and Buckland House, England, Conference, 1950.

(d) Values suggested by the Harriman, New York, Conference, April 1953.

(e) The original values were based on chemical toxicity. The present values are based on radiation exposure and are considered to be safe from the standpoint of chemical toxicity.

(f) Obtained by a comparison of recommended values with the calculated values.

(g) Values of ^{3}H for air concentration reduced by a factor of 2 to take into account absorption through the skin.

(h) Values of μc and μc/c.c. are given for the parent element. The daughter elements are assumed to reach the appropriate fraction of equilibrium with the parent after it is taken into the body.

(j) The value, 10^{-7} μc/c.c., refers to Rn when the daughter products are in equilibrium in the inhaled air and is an exception to the rule stated under (h) above. The $(MPC)_a$ value for Rn free of daughter products would be considerably larger.

(m) The values of q in parentheses were obtained from the fractions,

$$\frac{(MPC)_w^{GI} \times q}{(MPC)_w} \text{ and } \frac{(MPC)_a^{GI} \times q}{(MPC)_a}$$

All the values of q in column 4 give the μc in the total body exclusive of the amount in the gastrointestinal tract.

(r) The curie of natural uranium is considered to correspond to $3{\cdot}7 \times 10^{10}$ dis/sec from ^{238}U, $3{\cdot}7 \times 10^{10}$ dis/sec from ^{234}U and 9×10^{8} dis/sec from ^{235}U. The curie of natural thorium is considered to correspond to $3{\cdot}7 \times 10^{10}$ dis/sec from ^{232}Th and $3{\cdot}7 \times 10^{10}$ dis/sec from ^{228}Th. It is considered that none of the other daughter products of ^{238}U or ^{232}Th are present at the time of ingestion or inhalation.

(s) The daughter products in these cases are isomers in an excited state.

3. *Unidentified radioisotopes*

The last two values listed in Table C.VIII are for "any fission mixture (β, γ)" and "any mixture of α emitters". These values are convenient to use when the identity of the radioactive contaminant has not been established. They are safe for use for short periods of time—a few months—regardless of the radioactive contaminant. If the gross β, γ and α counts of air and water samples do not exceed these values, their use may obviate the necessity for expensive and time-consuming radiochemical analyses. These values are safe for indefinite use with exceptions as follows: (1) the safety factor of 10 mentioned previously should be considered when the values are applied to large populations, and (2) a few radioisotopes have lower values, namely:

(*a*) 10^{-7} μc/c.c. of water is safe for any mixture of β, γ emitters, and all α emitters except ^{226}Ra.

(*b*) 10^{-9} μc/c.c. of air is safe for any mixture of β, γ emitters except ^{90}Sr.

(*c*) 5×10^{-12} μc/c.c. of air is safe for any mixture of α emitters except ^{239}Pu and ^{227}Ac.

4. *Maximum permissible values for a known mixture of radioisotopes*

It is considered that any mixture of the radioisotopes as listed in Table C.VIII is permissible, provided the accumulated body burden, $f_2 q$, in any organ, or the concentration in the contents of the gastro-intestinal tract, does not reach a value that delivers a dose which exceeds the maximum permissible dose-rate of 0·3 rem/week. Three examples are given below to indicate how maximum permissible concentrations of mixtures of radioisotopes may be estimated as follows:

(*a*) $\frac{1}{3} \times 8 \times 10^{-3}$ μc/c.c. ^{24}Na + $\frac{2}{3} \times 6 \times 10^{-3}$ μc/c.c. ^{35}S = $6{\cdot}7 \times 10^{-3}$ μc/c.c. in water.

This drinking water would result in approximate dose-rates of:

(1) 0·1 + 0·2 = 0·3 rem/week to the gastrointestinal tract.

(2) $\frac{1}{3} \times 0{\cdot}3 = 0{\cdot}1$ rem/week to the total body.

(3) $\frac{1}{3} \times 0{\cdot}3 + \frac{2}{3} \times \frac{6 \times 10^{-3}}{5 \times 10^{-3}} \times 0{\cdot}3 = 0{\cdot}34$ rem/week to the skin.

In these estimates the (MPC) values are assumed to correspond to a dose-rate of 0·3 rem/week although this is not necessarily the case.

(*b*) 0·15 rem/week external exposure to the total body + $\frac{1}{2} \times 10^{-4}$ μc/c.c. ^{45}Ca + $\frac{1}{2} \times 4 \times 10^{-3}$ μc/c.c. ^{59}Ni.

= $2{\cdot}05 \times 10^{-3}$ μc/c.c. in water + 0·15 rem/week external exposure.

This drinking water and external exposure would result in approximate dose-rates of:

(1) $0{\cdot}15 + \frac{1}{2} \times \frac{10^{-4}}{2 \times 10^{-2}} \times 0{\cdot}3 + \frac{1}{2} \times 0{\cdot}3 = 0{\cdot}3$ rem/week to the gastrointestinal tract.

(2) $0{\cdot}15 + \frac{1}{2} \times 0{\cdot}3 = 0{\cdot}3$ rem/week to the bone.

(3) $0{\cdot}15 + \frac{1}{2} \times \frac{4 \times 10^{-3}}{0{\cdot}3} \times 0{\cdot}3 = 0{\cdot}15$ rem/week to the liver.

(*c*) $\frac{1}{6} \times 6 \times 10^{-9}$ μc/c.c. ^{131}I + $\frac{4}{6} \times 10^{-7}$ μc/c.c. ^{32}P + $\frac{2}{6} \times 10^{-5}$ μc/c.c. ^{14}C = $3{\cdot}4 \times 10^{-6}$ μc/c.c. in air.

This contaminated air would result in approximate dose-rates of:

(1) $\frac{1}{6} \times 0{\cdot}6 = 0{\cdot}1$ rem/week to the thyroid (note that permissible exposure rate to thyroid is 0·6 rem/week).

(2) $\frac{4}{6} \times 0{\cdot}3 = 0{\cdot}2$ rem/week to the bone.

(3) $\frac{2}{6} \times 0{\cdot}3 = 0{\cdot}1$ rem/week to the fat.

(4) $\frac{1}{6} \times \frac{6 \times 10^{-9}}{>6 \times 10^{-9}} \times 0{\cdot}6 + \frac{4}{6} \times \frac{10^{-7}}{10^{-7}} \times 0{\cdot}3 + \frac{2}{6} \times \frac{10^{-5}}{10^{-5}} \times 0{\cdot}3$ = between 0·3 and 0·4 rem/week to the gastrointestinal tract.

In the above problems, the simplifying assumption is made that the dose is negligible to organs other than the critical organs listed in column 3 of Table C.VIII. This introduces some error; for example, in problem (*c*) the bone receives a small amount of radiation from ^{131}I and ^{14}C, but this is small compared to the dose from ^{32}P.

5. *Parent-daughter radioisotopes*

In several cases values are given for parent-daughter relations, such as ^{90}Sr + ^{90}Y, ^{140}Ba + ^{140}La, ^{144}Ce + ^{144}Pr, etc. In all cases except ^{222}Rn or ^{220}Rn + daughter products, the maximum

permissible body burden and maximum permissible concentration values in water and air are given in terms of the parent element only; for example, μc of ^{90}Sr/c.c., and not μc of ^{90}Sr + ^{90}Y/c.c. It is assumed in these cases that the appropriate fraction of equilibrium of the daughter is reached with the parent element after fixation of the parent takes place in the critical body organ. It is further assumed that the daughter element remains in the critical organ after its birth for a length of time determined by its biological and radioactive half-life, and, consequently, contributes to the total dose. In the case of ^{222}Rn + daughter products the value of 10^{-7} μc/c.c. refers to ^{222}Rn in equilibrium with ^{218}RaA, ^{214}RaB, ^{214}RaC, and ^{214}RaC′, so that the $(MPC)_a$ value of ^{222}Rn free of its daughter products would be considerably greater. For the 10^{-7} μc/c.c. of ^{222}Rn, daughter products are in equilibrium in the inhaled air only down to the long-lived 22-year ^{210}RaD, and for ^{220}Rn all the daughter products are in equilibrium. In the case of ^{226}Ra, none of the daughter products are included in the 8×10^{-12} μc/c.c. of inhaled air, but the daughter products grow while the radium is in the body and 55 per cent of the daughter products down to ^{210}RaD are assumed to be retained in the bone. ^{210}RaD plus daughters contributes 1·54 per cent of the total dose. In the case of "U-natural" and "Th-natural", it is assumed that the equilibrium mixture (^{238}U, ^{235}U and ^{234}U in the case of uranium, and ^{232}Th and ^{228}Th in the case of thorium) is present at the time of body intake, and all other chemical elements have been removed or considered separately. The short-lived daughter products are assumed to reach equilibrium with the parent element after the parent element is deposited in the body.

6. *Type of radiation contributing to the dose*

The notation following the radioisotope—β, β^+, γ, α, e^-, K, X—refers to β, positron, γ, α, internal conversion electron, K-capture and X-radiation, respectively, and indicates the type of ionizing radiation from the source that contributes to the dose in the critical body organ. Annihilation radiation is assumed in the case of positrons.

7. *Soluble and insoluble compounds*

In all cases the values in Table C.VIII are for soluble compounds, except where indicated otherwise in column 2. Values for other insoluble compounds may be found by substituting the value of $\Sigma E(\mathrm{RBE})\mathcal{N}$ (2nd values in parentheses in column 5 of Table C.V), in the general equation $(MPC)_a = 2 \times 10^{-9}/\Sigma E(\mathrm{RBE})\mathcal{N}$.

8. *Radiation* v. *chemical toxicity*

A radioelement becomes a problem of chemical toxicity rather than one ot radiation hazard when the maximum permissible values based on chemical toxicity are smaller than the maximum permissible values based on the radiation hazard. In all cases in Table C.VIII, with possible exception of uranium—see reference (e)—the specific activities are so high that the radiation hazard is of primary concern.

9. *The period of exposure and application of safety factors to values in Table C.VIII*

The values in Table C.VIII are considered to be applicable to occupational exposure without any additional safety factor. No particular harm is to be expected if these values are exceeded for a short period of time—a few weeks—and no readily detectable biological damage is expected to result if the average body burden or the average maximum permissible concentration values over a long period of time do not exceed these values. However, some detectable biological changes may be expected if these maximum permissible values are maintained over the lifetime of many individuals, and as a

result a factor of safety of 10 is recommended for prolonged exposure of a large population. It is believed that, when using the values given in Table C.VIII without the addition of the safety factor of 10, biological changes would probably be less than those to be expected from many common and accepted insults to the body, such as over-eating, dusty homes, excessive use of stimulants, etc. However, as pointed out in the Introduction, all unnecessary exposure to ionizing radiation should be avoided and the safety factor of 10 is recommended when permanent installations are planned which may introduce large quantities of radioactive material into the environment where large numbers of people may be exposed. Whilst the values proposed for maximum permissible exposures are such as to involve a risk which is small compared to other hazards of life, nevertheless in view of the unsatisfactory nature of much of the evidence on which our judgments must be based, coupled with the knowledge that certain radiation effects are irreversible and cumulative, it is strongly recommended that every effort be made to reduce exposures to all types of ionizing radiations to the lowest possible level.

The values in Table C.VIII are based on continuous exposure. Since many of the occupational exposures would last only a fraction of the week (*i.e.* 8 hours/day, during which time it is assumed the body intake of air and water is half the daily requirement, 5 days/week and 50 weeks/year), the maximum permissible concentration values in Table C.VIII could be multiplied by a factor of 3 for the usual occupational exposure (*i.e.* $2 \times 7/5 \times 52/50 = 3$).

This report applies only to maximum permissible values for continuous exposure. Exposures of individuals for a few days to air and water concentrations 10 times those listed in Table C.VIII would not be harmful or any cause for alarm provided the average concentration over any interval of a year does not exceed these recommended values.

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D. REPORT OF INTERNATIONAL SUB-COMMITTEE III ON PROTECTION AGAINST X RAYS GENERATED AT POTENTIALS OF 5 kV UP TO 2 MV

I. INTRODUCTION

In this report, which is based upon the Codes of Practice in operation in various countries, the main emphasis has, in accordance with the Commission's policy, been put on the basic requirements of radiation protection, leaving the expansion of detailed technical requirements to national committees. It has, however, been considered desirable to introduce certain graphs and tables into the Appendix as examples from which the necessary numerical values for radiation protection can be obtained.

In addition to an extensive revision of the previous recommendations which were intended primarily for medical users of X rays, the Sub-Committee has inserted a section dealing with the industrial and research uses of X rays.

All previous radiation-protection recommendations were designed exclusively for the protection of personnel working with radiation. In view, however, of the increasing use of radiation for diagnostic and therapeutic purposes, it appears appropriate to give some guidance regarding the protection of patients. In considering possible genetic damage, it is important to note that already, in some countries, the total dose given to patients—at least so far as X-ray diagnosis is concerned—is much greater than the total dose of those who are occupationally employed with radiation. Accordingly, at a future date, it may prove desirable to introduce a radiation certificate upon which all doses of radiation received by a patient during his lifetime are recorded.

The exposure of human beings to X rays associated with shoe-fitting machines involves inherent risks. It is, therefore, recommended that this should be limited to strictly necessary medical procedures under the supervision of qualified experts.

Attention has also been given to the question of the radiation exposure of people in the neighbourhood of equipment not primarily intended for the production of X rays, for example, television equipment, transmitting valves, high-tension rectifying valves, image convertors and oscillographs. Since the number of television viewers is increasing rapidly, a value is now recommended for the maximum permissible dose-rate at the surface of the equipment.

It should be stressed that recommendations for the installation and operation of X-ray equipment, or for dealing with radioactive materials, are by no means sufficient in themselves to guarantee adequate protection. Such protection depends largely on the expert knowledge of the staff and on their co-operation in carrying out the instructions prepared by their supervisor in the interests of radiation protection.

II. DEFINITIONS OF TERMS

The following terms appear only in this Section D of the Commission's report and are therefore defined here. Other terms used are defined in Section A.V.

Tube housing: housing which surrounds the tube itself, or the tube and parts of the X-ray apparatus (for example, transformer). The tube housing limits the major portion of the radiation emerging from the tube to the "useful radiation" (see definitions in Section A). The housing is made of metal, or has to be metallised, and is connected to earth.

Fully-protective tube housing: housing in which the "leakage radiation" (see Section A) is reduced to about 6 mr/hour, corresponding to 300 mr/week for 48 hours' exposure time, at the surface of the tube housing when the tube is continuously operated, with closed window, at its maximum rated current for the maximum rated voltage.

Highly-protective tube housing: housing in which the leakage radiation is reduced to at most 100 mr/hour, corresponding to 300 mr/week for 3 hours' exposure time, at the surface of the tube housing, when the tube is continuously operated, with closed window, at its maximum rated current for the maximum rated voltage.

Therapeutic-type tube housing: housing in which the leakage radiation is reduced to at most 1 r/hour at a distance of 1 metre from the X-ray source and 1 r/minute at any point on the surface of the housing, when the tube is continuously operated, with closed window, at its maximum rated current for the maximum rated voltage.

(It should be realised that, in some cases of therapeutic treatment, patients are so positioned relative to the tube that parts of their bodies are in actual contact with the tube housing and that, in certain designs of tube, the distance from the X-ray source to the housing may, in places, be as little as 5 cm. Accordingly, if the patient is in contact with such sections of the tube housing, it will be necessary to increase the protection, otherwise parts of the patient's body may receive doses up to several hundred röntgens during a course of treatment.)

Diagnostic-type tube housing: housing in which the leakage radiation is reduced to at most 100 mr/hour at a distance of 1 metre from the X-ray source when the tube is continuously operated, with closed window, at its maximum rated current for the maximum rated voltage.

Work (or occupancy) factor (f): fraction of the total working time per week (taken as 48 hours), during which personnel are present in areas where radiation hazards exist.

Inherent filtration: radiation filtration of the useful beam by the X-ray tube, tube-housing window and insulating oil or air. The inherent filtration should be measured in the materials recommended by I.C.R.U. and at the highest-operating potential of the X-ray tube in question.

It is suggested that this filtration be determined by comparison of the narrow-beam absorption curve of the tube in question and a standard narrow-beam absorption curve obtained with negligible filtration.

III. PLANS FOR X-RAY INSTALLATIONS

1. Plans for a new X-ray installation or for a modification of an existing installation involving structural shielding should be discussed, before building is commenced, with the appropriate protection organisation or health physicist or other qualified expert.

2. Protection can be achieved by distance and by protective barriers. Where the cost of protective barriers becomes an important consideration, as, for example, with high-voltage X-ray equipment, the siting of the installation with respect to other occupied space may permit economies to be effected. In special cases, the distances involved may be such as to permit the barrier thicknesses to be reduced to zero. These distances, based upon an assumed exposure time of 48 hours/week in the direction of the useful beam, are indicated in Table D.VII of the Appendix (Sub-Section XI.5).

3. Figs. D1 to D4 of the Appendix (Sub-Section XI.1) represent basic absorption data for the computation of protective barrier thicknesses. Examples of barrier thicknesses required are given in Fig. D5 and Tables D.I to D.V, D.VIII and D.IX of the Appendix. The tables are based on an exposure time of 48 hours/week at the voltages and currents indicated. (It is appreciated that such detail can be dealt with more appropriately by National Protection Committees.)

4. Protection against the useful beam should be calculated without considering the patient, phantom or other object in the beam.

5. Protection against stray radiation requires, in general, smaller barrier thicknesses than would be necessary for the corresponding useful beam. Accordingly, the amount of structural protection required in any instance can be appreciably reduced by using protective tube housings and introducing mechanical restrictions on the angulation of the tube. The method of computing the thicknesses of secondary protective barriers is given in the Appendix (Sub-Section XI.3 and 4).

6. In order to render an X-ray installation completely foolproof, in so far as the protection afforded by barriers is concerned, the protection should be computed for the maximum rated voltage and current, for the shortest distance from the X-ray source to occupied space, and for an exposure period of 48 hours/week. In some circumstances, the operating conditions may be modified in such a manner that less rigorous conditions can be imposed and the protection reduced accordingly. For example, there may be mechanical restrictions on the angulation of the tube or limitations in the daily or weekly operating time of the tube. In such circumstances, a warning notice shall be exhibited prominently in the X-ray department drawing attention to the limitations imposed, thus:

(*a*) the useful beam shall not be directed at the ceiling;

(*b*) the total exposure time shall not exceed one hour per day or six hours per week; and

(*c*) this wall offers protection against stray radiation only. The lead equivalent is 0·5 mm at 80 kV.

7. The number and size of openings from the radiation room to occupied space should be reduced to a minimum. These requirements can be relaxed when the walls face unoccupied space.

8. When assessing the amount of protection required, the possibility of multiple exposure from several different X-ray tubes should not be overlooked.

9. In all protective barriers, care should be taken to ensure that the protection is not reduced at joints, fixing nails or bolts, etc. In such places there should be adequate overlapping of the protective material. Holes in the protective barriers for pipes, conduits, louvres, etc., shall be provided with baffles so that the protection is not impaired. Such holes should not be in the path of the useful beam.

10. Final plans of an X-ray installation should have the thicknesses and specifications of all protective barriers plainly marked. The positions of all windows, doors, pipes and louvres shall be indicated in so far as they pertain to the protection requirements.

Such plans should have the approval of the appropriate protection organisation or health physicist or other qualified expert.

IV. SURVEY AND MONITORING OF X-RAY INSTALLATIONS

1. *Radiation survey*

Routine operation of any X-ray installation involving structural protection shall be deferred until a radiation survey has been made and the installation found to comply with the recommendations.

A survey shall be made by the recognised protection organisation or health physicist or other qualified expert. A survey shall also be made after every change in an existing installation. "Change" should here be construed to mean a change whereby the X-ray output, work-factor or maximum operating potential has been increased, or the protection of a barrier altered.

Unless personnel monitoring has been regularly carried out, re-survey of an installation should be carried out periodically. Re-surveys may be done less frequently if personnel monitoring has been carried out regularly.

2. *Procedure for radiation survey*

(*a*) *General examination*

(i) The completed installation should be compared with the plans and specifications previously approved.

(ii) If the protection depends on mechanical restrictions on the orientation of the X-ray beam or on limitations of the conditions or period of excitation of the X-ray tube, the survey shall include an inspection to see if these restrictions are actually imposed. In particular, the position of the control panel with respect to the useful beam shall be noted.

(iii) All interlocks and warning signs shall be inspected to ensure that they are operating properly.

(iv) The inspector should watch the methods of operation of the X-ray equipment at the time of the survey, to satisfy himself that proper precautions are being taken against radiation hazards.

(v) All protective devices, such as gloves, aprons and electrical interlocks, which may become defective in use, shall be examined at least every six months. A qualified expert is not required for this inspection. Full records of each inspection shall be filed for reference purposes.

(*b*) *Measurements of the local dose (or dose-rate)*

(i) In carrying out a radiation survey it is often useful to make a preliminary investigation by means of a sensitive fluorescent screen or fluorescent-screen photometer. Other preliminary measurements may be made with ionization chambers, or suitable Geiger-Müller counters, or the like.

(ii) For the final survey, ionization chambers or other suitable equipment having a low variation in sensitivity with the quality and direction of the radiation and also a reliable constancy of sensitivity, should be used.

Further details regarding the methods which might be adopted in carrying out a radiation survey are given in the Appendix, Sub-Section XI.8.

(*c*) *Miscellaneous*

(i) A study should be made of the personnel monitoring technique, if one is used.

(ii) Whenever radiation hazards are found to exist, they shall be eliminated before the X-ray apparatus is used.

(*d*) *Report on radiation survey*

(i) The results of a survey should be submitted in a formal written report to the authority requesting the survey and should be seen by the head of the X-ray establishment concerned.

(ii) Copies of each report should be filed by the inspector or health physicist and by the authority requesting the survey.

V. GENERAL WORKING CONDITIONS AND PERSONNEL TESTS

1. *General principles*

(*a*) *Responsibility*

The responsibility of the head of the department for the provision of working conditions in accordance with any regulations, recommendations or codes of practice on radiation protection in operation in his own country, has been dealt with in Section A.VIII.1. The duty of the workers in carrying out the instructions which have been drawn up in the interests of radiation protection has also been mentioned.

(*b*) *Maximum permissible doses*

The maximum permissible doses, which are recommended for external radiations, are given in the report of Sub-Committee I.

The values applicable to X-ray workers dealing with radiations up to 2 MV are:

(i) *Whole-body irradiation*

Skin: 600 mr/week in the basal layer of the epidermis.

Blood-forming organs, gonads and eyes: 300 mr/week in a significant volume.

For the purposes of the recommendations in this report, it will be assumed that the above requirements are met when the dose measured in free air (that is, without back-scattering) does not exceed 300 mr/week.

(ii) *Partial irradiation of the body*

Hands and forearms, feet and ankles, head and neck: 1500 mr/week in the skin (less in deeper tissues), provided that, in the case of irradiation of the head, the dose in the lens of the eye shall not exceed 300 mr/week. In all cases the skin dose refers to the significant skin area receiving the highest weekly dose.

(*c*) *Maximum permissible dose-rate for continuous exposure*

In some cases, when the X-ray equipment is operating continuously, protection must be provided on the assumption that a worker may be exposed at a constant dose-rate for the entire working week. On the basis of 48 hours' exposure per week, the dose-rate corresponding to the maximum permissible dose of 300 mr/week in free air is about 6 mr/hour (0·1 mr/minute, 10^{-4} r/minute). The computations of protection which are dealt with in the Appendix refer, in the main, to 48 hours/week exposure.

2. *Personnel tests*

The head of the department shall ensure that adequate physical examinations and radiation monitoring of personnel are carried out.

(*a*) *Region of applicability*

The following recommendations regarding physical examinations and personnel monitoring are intended to apply to personnel who are liable during the course of their duties, to receive doses in excess of 1/10 of the maximum permissible weekly dose. Physical examinations and personnel monitoring can be dispensed with if the weekly dose, as estimated from the preliminary site monitoring and the work-factor, can never exceed the above value.

(*b*) *Health surveillance*

The need for a pre-employment physical examination and blood count, the details regarding the scope of the examination, and the need or otherwise of periodic tests, are dealt with in Section A.VIII.4.

(*c*) *Personnel monitoring*

Personnel monitoring by means of film badges or ionization chambers should be continuous or periodic, according to the circumstances.

(i) *Continuous measurements*

When the safety of personnel depends upon the adoption of a certain working procedure or the proper functioning of equipment rather than upon the provision of adequate protective barriers, radiation monitoring should be continuous. Examples of radiological operations in which variable procedures are adopted and which consequently involve greater hazards are angiocardiography and bronchography.

Since the personnel dose can be very different for different parts of the body, there is a possibility of making false deductions from a single measurement. Consequently, it may be necessary to use more than one film badge or ionization chamber, depending on the circumstances.

(ii) *Periodic measurements*

In those cases where the protection is entirely of a fixed structural nature and site monitoring has revealed satisfactory conditions, personnel monitoring at intervals not exceeding three months should suffice.

3. *Radiation warning signs*

See Section A.VIII.5.

VI. PROTECTION FOR X-RAY DIAGNOSTIC DEPARTMENTS

1. *Equipment for fluoroscopy*

(*a*) The protective tube housing shall conform to the requirements for diagnostic housing. (See Sub-Section D II.)

The type of housing should be indicated on the housing itself.

(*b*) The tube protective enclosure should be provided with a diaphragm which leaves a margin of at least 5 mm of unilluminated fluorescent screen with the screen at its greatest distance from the tube for any angulation of the table.

(*c*) Apertures or cones which serve to limit the useful beam should provide the same degree of protection as the tube housing.

(*d*) Tube, aperture and screen should be connected together in such a manner that the useful beam cannot fall outside the screen.

(*e*) The fixed total filter equivalent values should be at least 2 mm aluminium, and should be based on the value obtained at the highest voltage of the X-ray apparatus. For thick parts of the body of an adult, 3 mm should be used.

(*f*) The fluorescent screen shall be covered with a protective glass sheet of lead equivalent of at least 1·5 mm for 100 kV (peak). From 100 to 150 kV an additional lead equivalent of 0·01 mm per kV is required. (For protection without a patient in the beam a higher lead equivalent will probably be required.)

(*g*) It is essential to be able to switch the tube on and off from the examination place with aid of a switch operated by the hand, knee or foot.

(*h*) It is recommended that all couches and stands for fluoroscopy are provided with an adequate arrangement for protecting the operator against scattered radiation from the patient. This should take the form of an apron made of three or more overlapping parts to facilitate palpation.

(*i*) The use of a timer to measure the fluoroscopy time is recommended.

2. *Procedure for fluoroscopy*

(*a*) Persons who regularly work in the radiological department shall not be asked to assist in holding weak patients or children during fluoroscopy. If necessary, children should be held by their parents or the person accompanying them. Such persons should be protected, particularly with respect to the gonads and hands. Motion-restricting devices should be used as far as possible.

(*b*) Before a fluoroscopic examination is begun, the eyes must be sufficiently dark-adapted. In order to work with the lowest possible dose-rate, the adaptation period should be at least ten minutes. A smaller time may be used if there has been preliminary adaptation using red goggles.

(*c*) Notwithstanding that the X-ray equipment conforms in every respect to the requirements of these recommendations, it may be necessary, in certain fluoroscopic procedures, to wear protective clothing, such as gloves, aprons, coats and shinbone-protectors, in order that the maximum permissible doses are not exceeded.

(*d*) In all normal fluoroscopic work at potentials of less than 100 kV, the lead-equivalent of protective clothing should be not less than 0·25 mm.

(*e*) Protective gloves should be worn during each examination. These should cover the whole hand, including back, palm, fingers and wrist. The use of washable linings in these gloves is recommended.

Protective gloves designed for work with bleeding or vomiting patients, or with persons carrying an infectious disease, or for work in the operating theatre, must be washable both inside and out.

3. *Equipment for radiography*

(*a*) For radiographs of thick parts of the body of adults a total filter of at least 3 mm of aluminium should be used. For other parts 2 mm should be used.

(*b*) An automatic switch should be incorporated.

(*c*) X-ray exposure should in general be capable of being controlled from the control panel only, except in the case of special techniques when it is necessary to be able to control the radiation from the couch.

(*d*) The patient should be observable from the control panel.

4. *Procedure for radiography*

Persons who regularly work in the radiological department shall not be asked to assist in holding weak patients or children during radiography. If necessary, children should be held by their parents or by the person accompanying them. Such persons should be protected, particularly with respect to the gonads and hands. Motion-restricting devices should be used as far as possible.

5. *Other types of diagnostic work*

(*a*) *Dental radiography*

(i) *Equipment*

The installation should be so built that the operator of radiographic equipment up to 70 kV can remain at least 1·0 m (over 70 kV, 1·50 m) from tube and patient.

For more than 100 mA min (6000 mAs) per week special protective screens are necessary, except where the distance between operator and tube is more than 3 m. Only the patient shall be in the useful beam.

(ii) *Procedure*

During radiography, the film should be fixed in position if at all possible; otherwise it should be held by the patient or by a person who is not habitually exposed to radiation.

The tube housing shall not be held by hand during exposure.

Fluoroscopy is strongly deprecated.

(*b*) *Transportable diagnostic equipment up to* 100 *kV*

(i) All transportable equipment should be provided with cones or with other restricting devices so that the smallest anode skin distance is normally at least 30 cm (12 in.).

(ii) The cone or other restricting device should be detachable for occasional contact radiographs, but its construction should be such that, in this case, the absence of the cone or other restricting device is quite evident. It should be noted that damage has occurred to workers and patients from contact radiography.

(iii) At least 1·5 mm aluminium equivalent should be provided as a fixed total filter.

(iv) The minimum distance of the operator from tube and patient should be 1·5 m. The operator shall not stand in the useful beam. Fluoroscopy is strongly deprecated.

(*c*) *Mass-radiography*

Mass-radiographic equipment shall be so built that personnel are adequately protected even without protective clothing.

VII. PROTECTION FOR X-RAY THERAPEUTIC INSTALLATIONS

1. *Equipment for deep therapy*

(*a*) The tube housing shall conform at least to the requirements for therapeutic-type protective housings. (See Sub-Section II of this report.) The type of housing should be indicated on the housing itself.

(*b*) Apertures or cones serving to limit the useful beam shall be so protected that the dose-rate of the emergent beam, outside the useful beam, shall not exceed 1 r/min.

(*c*) On each filter shall be marked the thickness of the filter itself as an added filter, as well as the total filtration given by the inherent filtration of the tube *and* of the additional filter, in order to avoid confusion. For safety, a filter indication system is recommended which permits easy recognition of the total filtration from the control panel.

(*d*) Unless it is possible to bring the X-ray equipment rapidly to full voltage after switching on, X-ray tube housings used for deep therapy shall be fitted with a shutter electrically operated from the control panel and of lead equivalent corresponding to that of the tube housing. The position of the shutter shall be indicated at the control panel by means of a signal.

(*e*) The door of the X-ray therapeutic room should be provided with an interlocking switch so that when it is opened the X-ray machine is shut off and when it is closed again the X-ray machine can be switched on only at the control panel.

(*f*) The patient should be under observation during the treatment. A speaker system for oral communication between patient and control room is recommended.

(*g*) For voltages over 100 kV, an ionization chamber (transmission monitoring chamber) built into the useful beam is recommended for observing the constancy of the radiation.

(*h*) The X-ray apparatus shall be provided with a time-switch to secure the correct treatment time, or an integrating dosemeter to secure the prescribed skin dose.

2. *Procedure for deep therapy*

(*a*) All restrictions in operating conditions shall be complied with.

(*b*) During deep-therapy treatments, nobody shall be in the treatment room except the patient.

(*c*) Before the treatment room is entered for setting up purposes, the X-ray tube shall, if possible, be switched off. If the tube cannot be switched off, the shutter shall be closed and the tube housing shall be of the highly- or fully-protective type, depending on the time spent in the treatment room. The tube shutter shall be capable of being operated from the control panel.

3. *Other types of therapeutic work*

(*a*) *Skin therapy or superficial therapy (including Grenz-ray therapy)*

Because of the high dose-rate, adequate protection against the useful beam shall be provided for tubes with beryllium windows or other windows of low inherent filtration. Special protective measures are required to avoid accidental irradiation of the personnel or the patient.

An audible or visible alarm shall indicate that the tube is in operation.

(*b*) *Short-distance therapy and contact therapy*

Tubes for short-distance therapy and contact therapy which are intended to be held by hand, shall have a highly- or fully-protective tube housing, depending on the total treatment time per week. (See Sub-Section II of this report.)

If the weekly exposure time for any one operator exceeds 20 min, the tube housing shall be provided with a hand shield for protection against the secondary radiation from the patient. Protective aprons (0·25 mm lead equivalent) and protective gloves (0·25 mm lead equivalent) should be worn during this work.

Tubes operating at voltages above 60 kV shall not be held in the hand. Such tubes can therefore be provided with therapeutic-type housings.

An audible or visible alarm shall indicate that the tube is in operation.

4. *Protection for therapy equipment up to* 2000 *kV*

The necessary protective thicknesses against useful beam and stray radiation should be obtained from the Appendix (Sub-Section XI). The values of the protective thicknesses depend to some extent on whether the useful beam has nearly the same direction as the beam of electrons (transmission anode) or is emitted at a greater angle (reflecting anode). Furthermore, these values are dependent on the wave form of the high voltage. The entrance to the treatment room can conveniently be in the form of a radiation maze, thus avoiding the necessity for heavily protected doors.

VIII. PROTECTION OF PATIENTS

1. *General rules*

By X-ray protection of the patient it is meant that the radiation exposure of the patient should be reduced as much as is compatible with successful diagnostic investigation or therapeutic treatment. In the case of non-malignant diseases, therapeutic treatment shall be employed with caution. The use of irradiation in the treatment of non-malignant diseases of the hands, *e.g.* fungus infection, should be avoided in the case of persons who deal with radioactive materials or are otherwise professionally exposed to radiation.

It shall be the duty of the doctor, before diagnostic or therapeutic measures are taken, to enquire whether the patient is professionally exposed to radiation.

The professional use by the patient of chemicals should also be taken into account.

In all therapeutic and diagnostic exposures, the integral dose should be kept as low as possible in order to protect the patient as much as possible from the radiation. Moreover, for this purpose, the tube-current, or the mAs value, and the number of examinations should be kept to a minimum. An automatic timer should indicate the length of the diagnostic or therapeutic exposure.

In all diagnostic investigations, the beam that strikes the patient should have a cross-section no larger than is essential for the investigation. This is of particular importance in fluoroscopy.

In all irradiations the gonads should be protected as much as possible by collimation of the beam or by protective screens.

In the case of children, it is important, in view of the little known action of radiation on growing tissues, to be cautious about repeating diagnostic examinations and to avoid too frequent systematic examinations of the whole of the body.

2. *Exposure in diagnostic examinations*

For ease and clarity in the consideration of exposures received in diagnostic work, it is recommended that tables be set up giving doses for radiography and fluoroscopy of lung, stomach, intestines, etc. Integral dose should also be taken into account as it gives a much clearer picture of the true exposure.

Special attention should be given to the possible hazards to pneumothorax patients who, as a result of the many screenings after each inflation, may receive large doses. The screenings should be replaced in part by radiographs.

An indication of the radiation dose-rates from a diagnostic machine can be obtained from the Appendix (Sub-Section XI.9, Tables D.X and D.XI).

3. *Radiation certificate*

In view of the continually increasing medical and technical use of ionizing radiation, it is desirable to accumulate information regarding the doses received both by individuals and by the population as a whole. As far as the individual is concerned, the information could be obtained by the introduction of a certificate in which are recorded details of all radiation exposure (medical and occupational) received through life. Probably it is impracticable to introduce such a certificate at present, but it is recommended that all radiologists and dentists keep records of the doses given, and the field sizes and radiation qualities used, in all diagnostic procedures. (It is presumed that such records are already available in the case of therapeutic procedures.)

IX. PROTECTION AGAINST X RAYS FROM APPARATUS FOR NON-MEDICAL APPLICATIONS

1. *General*

In the following paragraphs are included recommendations for protection against X rays used for non-medical applications, such as in industry and scientific research, and against all X rays not generated by X-ray tubes.

Many parts of the other sections, for example, the basic rules, the maximum permissible doses, the test of radiation hazards, and so on, apply equally well for non-medical applications of X rays.

2. *X-ray installations for industrial radiographic and fluoroscopic examinations*

(*a*) *Highly-protective installations*

A highly-protective installation shall conform with all the following requirements:

(i) The X-ray source and all objects exposed thereto shall be within a permanent total enclosure to which no person has access, or within which no person shall be permitted to remain, while the X-ray apparatus within it is in operation and which affords, under any reasonable operating conditions, adequate protection for all persons outside this enclosure.

(ii) The dose-rate at any accessible point outside the protective enclosure shall be not greater than 6 mr/h when the radiation beam is adjusted to give the maximum dose-rate at the point in question with the X-ray generator running at its maximum rated continuous current for the maximum rated voltage.

(iii) Reliable interlocks shall be provided to prevent anyone from entering the enclosure while the X-ray apparatus within it is in operation.

(iv) All door locks shall be provided with knobs or handles on the inside of the protective enclosure so that anyone who may have been locked in accidentally can leave the enclosure without delay. A mains switch shall also be provided inside the enclosure so that any person inside can ensure that no-one can operate the X-ray equipment whilst he is there.

(v) Visible or audible signals, or both, within the protective enclosure shall be actuated before the power to the X-ray tube can be turned on.

(vi) None of the protective shields, barriers, or enclosures should be subjected to unusual conditions of vibration, wear, breakage or deterioration.

(*b*) *Open installations*

(i) *Protective cabinet*

When the provision of a total enclosure in accordance with IX.2(*a*) is impracticable, the operator of an X-ray apparatus shall be shielded from useful and stray radiation by a cabinet or shield affording adequate protection throughout.

(ii) *Danger zone*

Other persons shall either be similarly protected or excluded from a danger zone round the X-ray apparatus and the article being examined. This danger zone shall be defined as the area within which the radiation dose-rate exceeds 6 mr/h.

(iii) *Direction of useful X-ray beam*

Where practicable the useful X-ray beam shall be pointed away from other working areas.

3. *X-ray diffraction (crystallography) units*

(*a*) *Hazards*

Special precautions shall be taken to avoid exposure to the intense useful beam. Owing to the low inherent filtration and the short target distance, the dose-rate may be so high that permanent skin injuries may be caused by a few seconds' exposure.

(*b*) *X-ray tube housing*

The X-ray tube shall be mounted in a highly protective housing.

(*c*) *Shutter and collimating system*

Each port or aperture of the X-ray tube housing should be provided with an automatic beam shutter, preferably so arranged that it can be opened only with the collimating system in place and the collimating system can be removed only with the shutter closed.

(*d*) *Protection against useful beam*

The X-ray camera should be provided with a protective screen which arrests the useful beam behind the specimen examined.

(*e*) *Separate room for installation*

Installations which are not provided with an adequate protection against useful and stray radiation shall be placed in a separate room in which no persons are permitted during the exposures.

(*f*) *Radiation monitoring procedure*

A ring film badge, worn on one of the fingers, should form part of the radiation monitoring procedure.

4. *Special rules for fluoroscopic installations*

(*a*) *Hand fluoroscope*

The so-called "hand fluoroscope" shall not be used for industrial purposes.

For research uses, the fluoroscopic screen shall be fixed on a rod so that the hands do not enter the useful beam. No part of the body shall be in the useful beam.

(*b*) *Movements of objects*

The movement of objects during fluoroscopic examination shall be effected by means of conveyor belts, turn-tables or other remotely controlled means.

In no case shall it be possible for the worker to place his hands in the useful beam.

5. *Shoe-fitting fluoroscopy*

The exposure of human beings to X rays associated with shoe-fitting machines involves inherent risks and should be limited to strictly medical procedures under the supervision of qualified persons.

X. PROTECTION AGAINST X RADIATION FROM SOURCES OTHER THAN ORTHODOX X-RAY APPARATUS

1. *Hazards*

Any electronic tube operating at potentials above 5000 volts shall be considered a possible source of X rays, and, if necessary, radiation barriers shall be provided.

2. *Sources of non-useful X rays may be:*

Cathode-ray tubes (oscillographs).
Electron microscopes.
Transmitting valves.
Rectifying valves.
Television tubes.
Image converters.

3. *Permissible dose rate*

If the dose-rate at any readily accessible point on the surface of the equipment does not exceed 0·6 μr/sec, neither personnel monitoring nor medical examinations shall be required.

But if the dose-rate is greater than 0·6 μr/sec suitable personnel monitoring should be carried out as prescribed by a qualified expert.

4. *Home television sets*

For home television sets the dose-rate shall not exceed 0·6 μr/sec at any readily accessible point on the surface of the apparatus.

XI. APPENDIX

1. *Radiation attenuation curves*

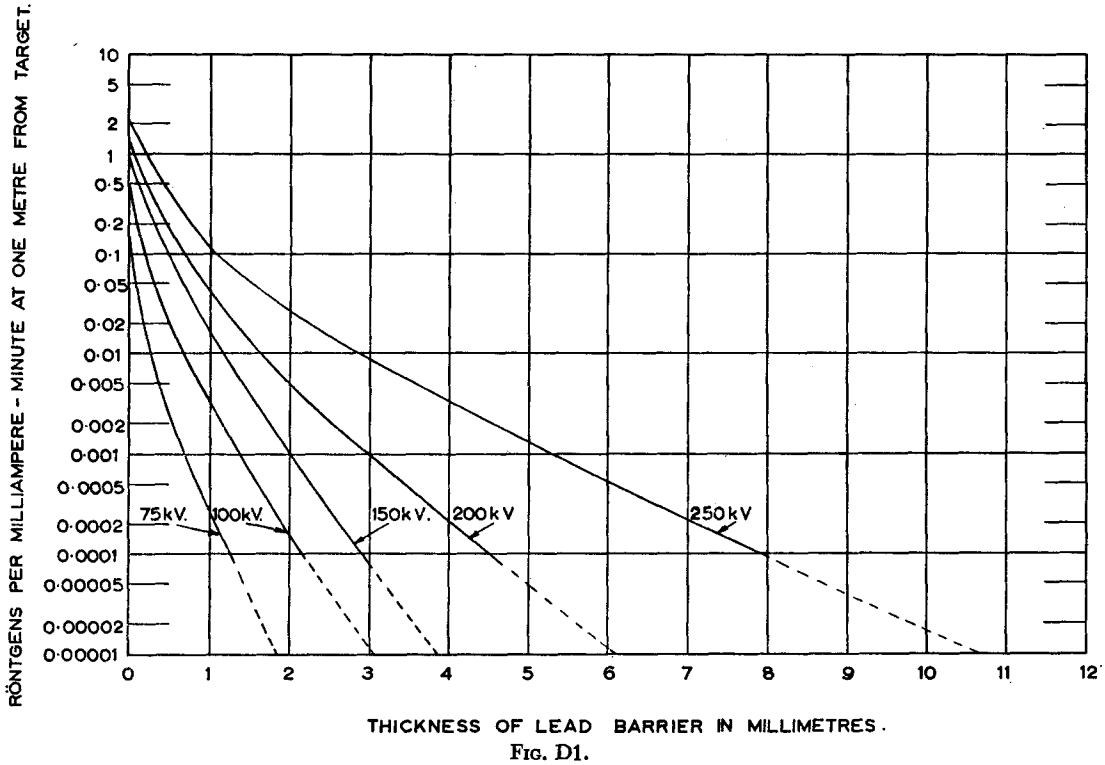

FIG. D1.

Attenuation in lead of X rays produced by potentials of 75 to 250 kV (peak).

The curves were obtained with a half-wave generator and a 90 deg. angle between the electron beam and the axis of the X-ray beam. The filter was 3 mm of aluminium for the 150, 200 and 250 kV (peak) curves and 0·5 mm of aluminium for the 75 and 100 kV (peak) curves. Direct-current potentials require 10 per cent thicker barriers than for the pulsating potentials given above. (C. B. Braestrup, 1944.)

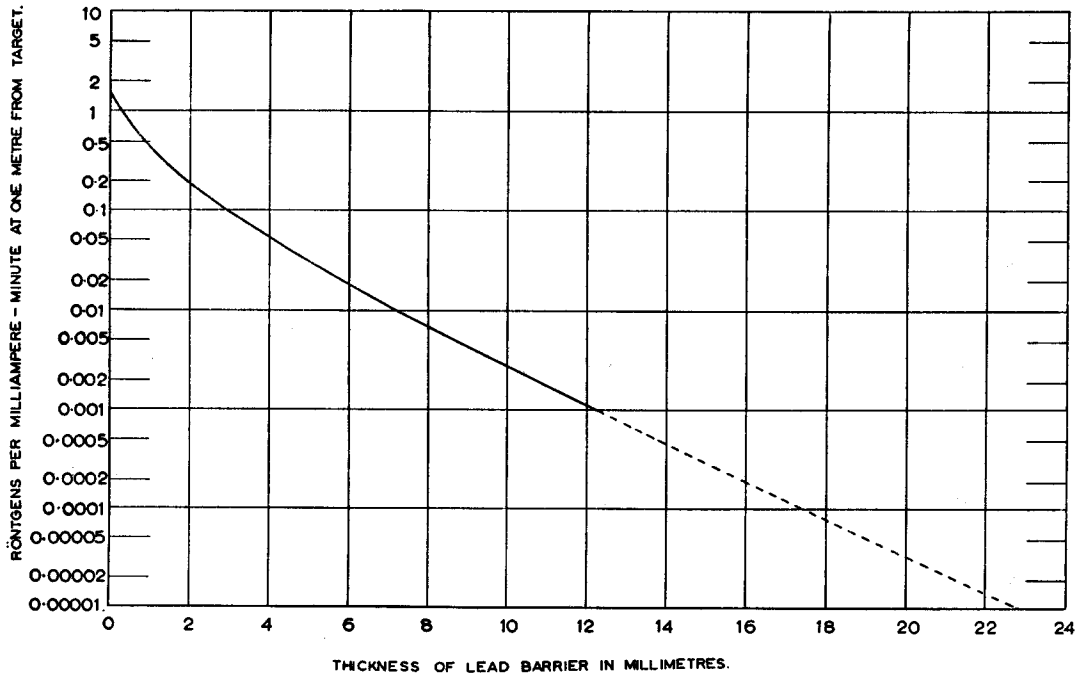

FIG. D2.

Attenuation in lead of X rays produced by a potential of 400 kV (peak).

The curve was obtained with a half-wave generator and with a 90 deg. angle between the electron beam and the axis of the X-ray beam. The filter was 0·4 mm of tin, 0·75 mm of copper, 2 mm of aluminium, plus the inherent filtration of the tube. (C. B. Braestrup.)

2. *Computations for the useful beam*

The curves of Figs. D1, D2, D3 and D4, which satisfy the "broad-beam" conditions, are chosen from the literature. The voltage waveform, direction of the X-ray beam with respect to the electron beam, and inherent filtration for each curve are listed below the corresponding figure. All these factors are important and should not be overlooked in the design of adequate, yet economical protection. The ordinates of the curves give the dose-rate of the useful beam beyond the barrier in röntgens per minute at a point 1 m from the target, for a target current of 1 mA. The abscissae give the thicknesses of the specified barrier material that reduce the dose-rate of the 1 mA beam, as shown by the ordinates. Barrier requirements at other distances and radiation outputs are computed on the basis of the dose-rate at 1 m. If the tube current is increased above 1 mA, the barrier requirements will be increased; if the distance between the tube and the point to be protected is increased, the barrier requirements will be decreased.

The figures, therefore, indicate directly the barrier thickness required to reduce the dose-rate to the permissible value of 6 mr/h (10^{-4} r/min) for 1 mA and at 1 m from the target.*

* See XI.6. Consideration of work factor.

By simple calculations the graphs may be used also for other conditions. For instance, if the actual distance is 2 m the distance factor reduces the radiation intensity by 4, and the barrier needs, therefore, only to reduce the radiation to 4×10^{-4} r/mA min at 1 m. On the other hand, if the actual current is 10 mA, the dose-rate is 10 times that for 1 mA, and the barrier must be such as would reduce the radiation from a 1 mA beam to $0{\cdot}1 . 10^{-4}$, or 10^{-5} r/min. In general, the required lead equivalent of the barrier may be obtained from the appropriate curve by using, as the ordinate, the dose-rate Y_u, where

$$Y_u = \frac{D^2}{i} . 10^{-5} \text{ (about)} \quad \ldots\ldots\ldots\

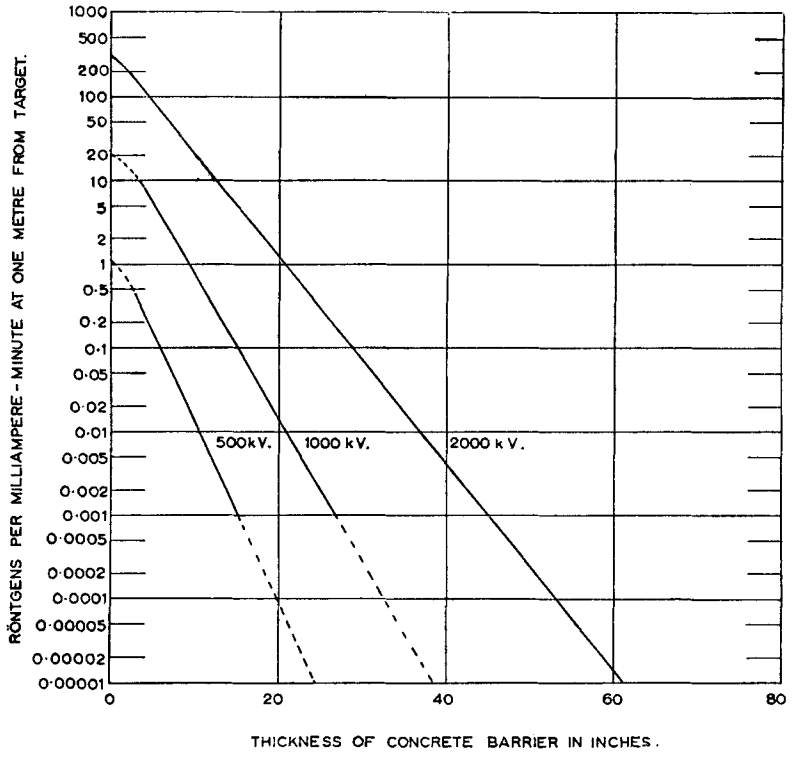

FIG. D4.

Attenuation in concrete of X rays produced by potentials of 500 to 2000 kV.

The 500 and 1000 kV curves were obtained with a direct-current generator. (H. O. Wyckoff, R. J. Kennedy and W. R. Bradford, 1948.)

The 2000 kV curve was obtained with a constant potential generator. (W. W. Evans, R. C. Granke, W. A. Wright and J. G. Trump, 1952.)

Concrete density was 2·35 to 2·4 g/cm³.

For example, suppose it is necessary to reduce the radiation to the permissible level at a point 8 ft from a target with a tube current of 10 mA at 100 kV. Here, $D = 8$ and $i = 10$ in equation (D1) gives

$$Y_u = \frac{(8)^2 \cdot 10^{-5}}{10} = 6 \times 10^{-5}$$

Using the ordinate value 6×10^{-5} on the 100 kV curve in Fig. D1, it is found that the lead barrier must be 2·4 mm thick.

From Fig. D5 (G. Singer, 1946) one can see directly the approximate lead thickness in millimetres of all tube voltages between 75 and 250 kV, for different numbers of hours-exposure per day, tube currents (mA) and distances between target and occupied place (metres).

Tables D.I, D.II, D.III, D.IV and D.V give the barrier requirements obtained according to equations D1 and D2 from the Figs. D1, D2, D3 and D4 for a number of typical conditions.*

* See XI.6. Consideration of work factor.

Approximate half-value layers of lead and concrete, where available, are also included for each tube potential, by which the barrier requirements for target currents other than those listed may be computed. For instance, if a target current of 5 mA is used at 100 kV with a

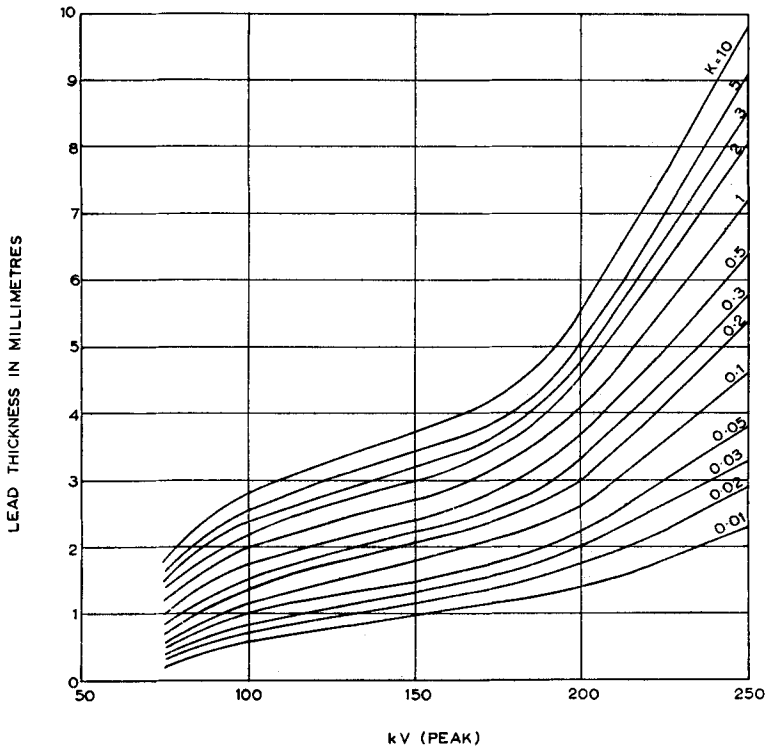

FIG. D5.

Thicknesses of lead required to reduce X-ray dose-rate of the useful beam to 6 mr/h (1×10^{-4} r/min), under indicated conditions (without consideration of air absorption).

Factor $K = \frac{h.i}{4.D^2}$, where h = number of hours of exposure per day, i = tube current in mA, D = distance between target and occupied place in metres. (G. Singer, 1946.)

target-to-personnel distance of 10 ft, the barrier will have to stop only one-half as much as the radiation delivered at the 10 mA target current. This does not mean that the barrier can be reduced by one-half, but that it can be reduced by one half-value layer (H.V.L.) of lead. In Table D.I the H.V.L. thickness for 100 kV radiation is given as 0·24 mm of lead. The barrier requirements for the reduced tube current will then be 2·2 — 0·24 = 2·0 mm of lead. Similarly a change in tube current by a factor of $4(=2^2)$ or $8(=2^3)$ would involve an increase or decrease of 2 or 3 H.V.L. in the barrier requirements, depending upon whether the current was raised or lowered from the tabulated value of 10 mA by those factors.

TABLE D.I

PRIMARY PROTECTIVE BARRIER REQUIREMENTS FOR 75 TO 300 kV (PEAK) PULSATING POTENTIALS[1] WITH TUBE CURRENT OF 10 mA

Target distance		Lead thickness with peak of					
		75 kV	100 kV	150 kV	200 kV	250 kV	300 kV
ft.	m	mm	mm	mm	mm	mm	mm
2	0·6	2·2	3·4	4·3	6·7	11·8	16·0
3	0·9	2·0	3·1	4·0	6·2	10·9	14·7
5	1·5	1·7	2·7	3·6	5·5	9·6	13·1
8	2·4	1·5	2·4	3·2	4·8	8·5	11·8
10	3·0	1·3	2·2	3·0	4·5	8·1	11·1
15	4·6	1·1	1·9	2·6	4·0	7·1	9·9
20	6·1	1·0	1·7	2·4	3·6	6·4	9·0
50	15·2	0·5	1·1	1·7	2·4	4·3	6·2
Approximate H.V.L. thickness measured at high filtrations		0·18	0·24	0·3	0·5	0·8	1·1
Radiation filter (mm of Al)		0·5	0·5	3·0	3·0	3·0	3·0

[1] X rays excited by direct-current potentials require approximately 10 per cent greater thickness than those given here for pulsating potential.

3. *Computations for the scattered radiation*

Very few data are available (W. Binks, 1943; N.B.S. Handbook 50, 1951; B. E. Keane and G. Spiegler, 1951; L. Lorentzon, 1954; R. Walstam, 1954; B. Lindell, 1954) on the quantity and quality of radiation scattered from various materials when irradiated under different conditions. Further investigations are desirable before any generalisations can be drawn. For the most practical cases, however, the scattered radiation measured at 1 metre from the scatterer does not exceed 0·1 per cent of the incident beam.

As absorption curves are not available for the scattered radiation, it is customary to use the same absorption curve for the scattered radiation as for the useful beam when the X-ray potential is less than 500 kV, and the 500 kV curve for all higher potentials. Any error is in the safe direction.

As the dose-rate must be reduced to 10^{-4} r/min at positions to be occupied by personnel, the radiation S in r/mA min. at 1 m from the target required to give such levels of scattered radiation is given approximately by

$$S_{500} = \frac{d^2D^2}{i} \cdot 10^{-3} \text{ for X-ray tube potentials of 500 kV or below} \quad \ldots\ldots(D3)$$

where D = distance between target and scatterer in feet;

d = distance between scatterer and position in occupied space in feet; and

i = tube current in mA.

For D and d in metres, the radiation S in r/mA min at 1 m from the target

$$S_{500} = \frac{d^2D^2}{i} \cdot 10^{-1} \quad \ldots\ldots(D4)$$

For 1000 kV potentials (output roughly 20 times as great as for 500 kV), the ordinate should be computed by the relation

$$S_{1000} = \frac{5 . d^2 D^2}{i} \cdot 10^{-5} \text{ (} d \text{ and } D \text{ in feet)} \quad \text{.....(D5)}$$

$$\text{or } S_{1000} = \frac{5 . d^2 D^2}{i} \cdot 10^{-3} \text{ (} d \text{ and } D \text{ in metres)} \quad \text{.....(D6)}$$

(The 500 kV attenuation curve is used to determine the barrier thickness.)

TABLE D.II

PRIMARY PROTECTIVE BARRIER REQUIREMENTS FOR 400 kV (PEAK) PULSATING POTENTIAL WITH REFLECTION TARGET[1]

Target distance		Lead thickness with target current of		
		1 mA	3 mA	5 mA
ft	m	mm	mm	mm
5	1·5	16·5	20	22
8	2·4	14·0	17·0	18·5
10	3·0	12·5	15·5	17·0
15	4·6	11·0	13·5	14·5
20	6·1	9·5	11·5	13·0
50	15·2	5·5	8·0	9·0
Approximate H.V.L. thickness measured at high filtration		2·0	—	—

[1] Radiation filter: 0·4 mm of tin, plus 0·75 mm of copper, plus 2 mm of aluminium.

For 2000 kV (output roughly 300 times as great as for 500 kV) the ordinate should be computed by the relation

$$S_{2000} = \frac{3 . d^2 D^2}{i} \cdot 10^{-6} \text{ (} d \text{ and } D \text{ in feet)} \quad \text{.....(D7)}$$

$$\text{or } S_{2000} = \frac{3 . d^2 D^2}{i} \cdot 10^{-4} \text{ (} d \text{ and } D \text{ in metres)} \quad \text{.....(D8)}$$

(The 500 kV attenuation curve is used to determine the barrier thickness.)

The abscissae corresponding to the ordinate values of equations (D3) to (D8) on the appropriate attenuation curve give the barrier thickness required for protection against scattering.

4. *Computations for the leakage radiation*

The leakage radiation is considerably reduced by the protection incorporated in the tube housing. Table D.VI shows the number of H.V.L.s necessary to obtain the reductions required at different distances. The H.V.L. for any specific X-ray tube potential used may be obtained from the proper column in Tables D.I, D.II, D.III, D.IV or D.V. For instance, if the distance from target to personnel is 10 ft. for a 250 kV (peak) therapy tube, Table D.VI indicates that approximately 4·1 H.V.L. are required. The 250 kV (peak) column of Table D.I shows the H.V.L. thickness to be 0·8 mm of lead. The required reduction is thus obtained with 4·1 × 0·8, or 3·3 mm of lead.

TABLE D.III

PRIMARY PROTECTIVE BARRIER REQUIREMENTS FOR 500 kV CONSTANT POTENTIAL WITH TRANSMISSION TARGET[1]

Target distance		Barrier thicknesses with target current of								
		1 mA			3 mA			5 mA		
		Lead	Concrete[2]		Lead	Concrete[2]		Lead	Concrete[2]	
ft.	m	mm	in.	cm	mm	in.	cm	mm	in.	cm
5	1·5	36	18·0	45	42	20·5	52	44	21·5	55
8	2·4	31	16·0	41	37	18·5	47	39	19·5	50
10	3·0	29	15·0	38	35	17·5	44	37	18·5	47
15	4·6	25	13·5	34	31	16·0	41	33	17·0	43
20	6·1	22	12·5	32	28	14·5	37	30	16·0	41
50	15·2	14	8·5	22	19	11·0	28	21	12·0	31
100	30·5	8	6·0	15	13	8·0	20	15	9·5	24
Approximate H.V.L. thickness measured at high filtration		—	—	—	3	1·5	3·5	—	—	—

[1] Radiation filter: 2·8 mm of tungsten, plus 2·8 mm of copper, plus 2·1 mm of brass, plus 18·7 mm of water.
The density of this concrete is 147 lb./ft.^{3} (= 2·35 g/cm^3).

TABLE D.IV

PRIMARY PROTECTIVE BARRIER REQUIREMENTS FOR 1000 kV CONSTANT POTENTIAL WITH TRANSMISSION TARGET[1]

Target distance		Barrier thicknesses with target current of								
		1 mA			3 mA			5 mA		
		Lead	Concrete[2]		Lead	Concrete[2]		Lead	Concrete[2]	
ft.	m	mm	in.	cm	mm	in.	cm	mm	in.	cm
5	1·5	123	30·5	78	131	32·5	83	136	33·5	85
8	2·4	113	28·0	71	120	29·5	75	125	30·5	77
10	3·0	107	27·0	69	115	28·5	72	120	29·5	75
15	4·6	97	24·5	62	105	26·5	67	110	27·5	70
20	6·1	91	23·0	58	99	25·0	64	104	26·0	66
50	15·2	69	18·0	47	77	20·5	52	82	21·0	53
100	30·5	53	15·0	38	61	17·0	43	66	18·0	46
Approximate H.V.L. thickness measured at high filtration		—	—	—	8	1·8	5	—	—	—

[1] Radiation filter: 2·8 mm of tungsten, plus 2·8 mm of copper, plus 2·1 mm of brass, plus 18·7 mm of water.
[2] These concrete thicknesses are for a concrete density of 147 lb./ft.^{3} (= 2·35 g/cm^3).

5. *Distance protection against useful X-ray beam*

In some installations it is possible to depend upon distance alone to give proper protection. Complete data for consideration of the air absorption are lacking. The data in Table D.VII have been computed for both inverse-square and air absorption reductions of the useful beam and have been based on zero barrier outputs given in the curves of Figs. D1, D2 and D3. The air-absorption coefficient was chosen for a photon energy equal to one-half of that of the

maximum X-ray photon energy. The table gives directly the distance, at which the dose-rate of the useful beam is 6 mr/h if no absorbing material other than air is in the beam.

TABLE D.V

PRIMARY PROTECTIVE BARRIER REQUIREMENTS FOR 2000 kV CONSTANT POTENTIAL WITH TRANSMISSION TARGET[1]

Target distance		Barrier thickness with target current of 0·25 mA			
		Lead		Concrete[2]	
ft.	m	in.	cm	in.	cm
5	1·5	8·4	21·0	45	115
8	2·4	7·8	20·0	41	105
10	3·0	7·5	19·0	39	100
15	4·6	6·9	17·5	37	95
20	6·1	6·5	16·5	35	90
50	15·2	5·3	13·5	29	75
100	30·5	4·3	11·0	24	60
Approximate H.V.L. measured at high filtration..		0·47	1·2	2·4	6·0

[1] Radiation filter equivalent to 6·8 mm lead.

[2] Concrete density 150 lb./ft.^{3} (=2·4 g/cm^3).

TABLE D.VI

HALF-VALUE LAYERS OF PROTECTIVE MATERIAL REQUIRED TO REDUCE THE LEAKAGE RADIATION TO THE PERMISSIBLE LEVEL

Distance from target to personnel		Number of half-value layers	
		Diagnostic-type tube housing	Therapeutic-type tube housing (based on 1 r/h at 1 m)
ft.	m		
3	0·9	4·2	7·5
4	1·2	3·4	6·7
5	1·5	2·8	6·1
6	1·8	2·3	5·5
7	2·1	1·8	5·1
8	2·4	1·5	4·7
9	2·7	1·0	4·3
10	3·1	0·8	4·1
12	3·7	0	3·6
15	4·6	—	2·9
17	5·2	—	2·6
20	6·1	—	2·1
25	7·6	—	1·5
30	9·2	—	0·9
40	12·2	—	0

6. *Consideration of work factor*

All the equations and tables in this appendix are based on a 48-hour working week. However, in many cases, the unit is only operated for one-third or one-sixth of the 48 hours each week.

Examples: (*a*) The tube is to be operated 16 hours/week at 15 mA. Then this target current will produce the same amount of radiation as a target current of 5 mA when the tube is operated for 48 hours. 5 mA is thus the target current to be used for the solution of the problem.

(*b*) Often a mechanical restriction is incorporated in the tube motion. If no such restrictions are permissible, it may still be possible to assign maximum times of irradiation of general areas. It may be possible to state, for instance, that the beam will be pointed toward the ceiling for a maximum of one-eighth of the 48 hours/week time (work factor = $\frac{1}{8}$). Then the primary protective barrier-thickness computed for the ceiling may be reduced by 3 H.V.L.

TABLE D.VII

DISTANCE PROTECTION FOR 50 TO 2000 KV X RAYS

Target current	Distance[1] for									
	50 kV		75 kV		100 kV		150 kV		200 kV	
mA	ft.	m	ft.	m	ft.	m	ft.	m	ft.	m
0·005	15	5	20	6	25	8	20	6	25	8
0·01	20	6	25	8	30	9	30	9	35	11
0·025	30	9	40	12	45	14	45	14	50	15
0·05	40	12	50	15	60	19	60	19	65	20
0·1	50	15	70	22	80	25	80	25	90	28
0·25	70	22	95	29	115	35	115	35	125	38
0·5	85	26	115	35	145	44	145	44	165	50
1	100	31	145	44	180	55	185	57	205	63
2	115	35	175	54	220	67	225	69	255	78
2·5	120	37	185	57	235	72	245	75	270	83
5	140	43	220	67	280	85	295	90	330	100
10	160	49	250	76	330	100	350	107	390	119
15	175	54	270	82	355	108	390	119	430	131
20	185	57	290	89	380	116	410	123	460	140
25	195	60	300	92	390	120	420	128	480	147

Target current	Distance[1] for									
	250 kV		400 kV		500 kV		1000 kV		2000 kV	
mA	ft.	m	ft.	m	ft.	m	ft.	m	ft.	m
0·005	25	8	25	8	30	9	90	28	195	60
0·01	35	11	35	11	40	12	115	35	240	74
0·025	55	17	55	17	60	18	175	54	370	113
0·05	70	21	70	21	75	23	220	68	460	140
0·1	95	29	95	29	110	34	275	84	540	165
0·25	135	42	135	42	155	48	380	116	720	220
0·5	170	52	170	52	200	61	460	140	850	260
1	215	66	215	66	255	78	550	168	980	300
2	270	83	270	83	320	98	640	195	1080	330
2·5	285	87	295	90	340	104	690	210	—	—
5	350	111	360	110	410	125	—	—	—	—
10	420	130	—	—	—	—	—	—	—	—
15	460	140	—	—	—	—	—	—	—	—
20	490	150	—	—	—	—	—	—	—	—
25	510	156	—	—	—	—	—	—	—	—

[1] These distances were computed by taking into account distance and air absorption. The air absorption was determined by assuming the radiation was monochromatic and of double the minimum wavelength of the polychromatic radiation given off by the tube at the indicated potential. The filtrations assumed were the same as the curves of Figs. D1, D2 and D3.

The figures of metres are rounded off.

7. *Lead equivalent of protective materials*

The lead equivalent of protective materials is dependent on the thickness of the material, the hardness of the X-radiation and to a limited extent on the size of the field. Accordingly, different values of the lead equivalent for broad beam or narrow beam are obtained.

Table D.VIII gives the lead equivalents of different thicknesses of concrete (density = 2·2 g/cm^3) for broad beams of X rays excited at potentials between 150 and 2000 kV. As regards other building materials, most of the tests were carried out with narrow beams. However, up to 400 kV X rays there is little difference between the lead equivalent values for narrow-beam and broad-beam conditions. Accordingly, experimental values obtained with X rays at voltages up to 400 kV are listed in Table D.IX.

In the case of lead-glass and lead-rubber, the absorption of X rays is largely due to their lead content, and therefore is related to the density of the material. There is little or no dependence on the hardness of the X-radiation or on the field size. In Fig. D6 are given curves which enable the lead equivalents of lead-rubbers and lead-glasses of different densities to be evaluated.

TABLE D.VIII

LEAD EQUIVALENT THICKNESSES OF CONCRETE FOR 150 TO 2000 kV X RAYS

Material	Mean density	Lead equivalent	X rays excited at peak voltages of						
			150 kV	200 kV	300 kV	400 kV	500 kV	1000 kV	2000 kV
	g/cm^3	mm	mm	mm	mm	mm	mm	mm	mm
Concrete									
2 parts ballast	2·2	1	85	80	60	50	—	—	—
2 parts sand		2	160	150	95	75	60	—	—
1 part cement		3	230	210	125	100	85	40	—
		4	295	275	150	120	105	55	—
		6	—	—	210	150	140	80	—
		8	—	—	260	185	165	100	—
		10	—	—	300	220	190	120	85
		15	—	—	—	300	250	160	115
		20	—	—	—	—	310	200	145
		50	—	—	—	—	650	385	315
		100	—	—	—	—	—	680	595
		150	—	—	—	—	—	1000	870

8. *Suggested methods of making a radiation survey*

(*a*) *Initial qualitative survey for possible radiation hazards*

A qualitative survey may be made with the aid of fluorescent screen, fluorescent screen photometer, Geiger-Müller counter or ionization chamber (dose-rate meter). If the X-ray room can be darkened, and the eyes adapted for 10 to 15 minutes, a simple fluorescent screen can be used which carries a lead marker in order to make the luminescence more easily recognisable. It should, however, be appreciated that the screen is not equally sensitive at all X-ray qualities. The method is excellent for diagnostic X rays, useful in the 180 to 200 kV therapy range, but of doubtful value for higher voltages. For average hardnesses, and after an adequate adaptation time, the smallest detectable luminescence corresponds to a dose-rate of about 3 mr/h (or 5×10^{-5} r/min) or may be less. Luminosity does not, therefore, necessarily mean that the permissible dose-rate is being exceeded.

The fluorescent-screen technique enables attention to be paid to suspicious bright spots in the radiation field and especially to narrow slits or small beams, which other types of detecting instruments might miss. Furthermore, the screen simplifies the task of tracing these radiation

leakages to their sources. In this connection, the emission of X rays which sometimes occurs from rectifying valves should not be overlooked.

TABLE D.IX

LEAD EQUIVALENT THICKNESSES OF VARIOUS PROTECTIVE MATERIALS FOR 150 TO 400 kV

Material	Mean density	Lead equivalent	Equivalent thickness of material			
			X rays excited at peak voltages of			
			150 kV	200 kV	300 kV	400 kV
	g/cm³	mm	mm	mm	mm	mm
Iron	7·9	1	11	12	12	11
		2	25	27	20	18
		3	37	40	28	23
		4	50	55	35	28
		6	—	—	48	38
		8	—	—	60	45
		10	—	—	75	55
		15	—	—	—	75
Barium concrete or plaster: 2 parts coarse $BaSO_4$ 2 parts fine $BaSO_4$ 1 part cement or 1 part coarse $BaSO_4$ 1 part fine $BaSO_4$ 1 part cement	3·2	1	10	14	14	13
		2	21	30	27	24
		3	35	45	40	35
		4	50	60	50	45
		6	—	—	70	65
		8	—	—	90	80
		10	—	—	120	100
		15	—	—	—	140
Barium concrete or plaster: 2 parts coarse $BaSO_4$ 2 parts sand 1 part cement or 1 part coarse $BaSO_4$ 1 part sand 1 part cement	2·7	1	17	22	22	18
		2	38	50	42	35
		3	65	75	60	50
		4	90	100	75	60
		6	—	—	105	85
		8	—	—	135	110
		10	—	—	165	130
		15	—	—	—	185
Brick (Daneshill red)	1·9	1	110	100	85	80
		2	200	190	140	110
		3	280	270	170	140
		4	370	350	210	160
		6	—	—	280	210
		8	—	—	340	260
		10	—	—	400	300
		15	—	—	—	400
Brick (Yellow stock)	1·6	1	130	130	100	90
		2	240	240	150	130
		3	340	340	200	160
		4	—	430	240	180
		6	—	—	320	240
		8	—	—	390	290
		10	—	—	460	340
		15	—	—	—	450
Coke breeze	1·2	1	140	150	120	110
		2	250	270	190	160
		3	350	380	240	200
		4	—	490	290	230
		6	—	—	380	300
		8	—	—	460	350
		10	—	—	550	400
		15	—	—	—	510

The determination of the value of the dose-rate at places of suspicious brightness can be done with ionization chambers, Geiger-Müller counters[1] and scintillation counters, if the field

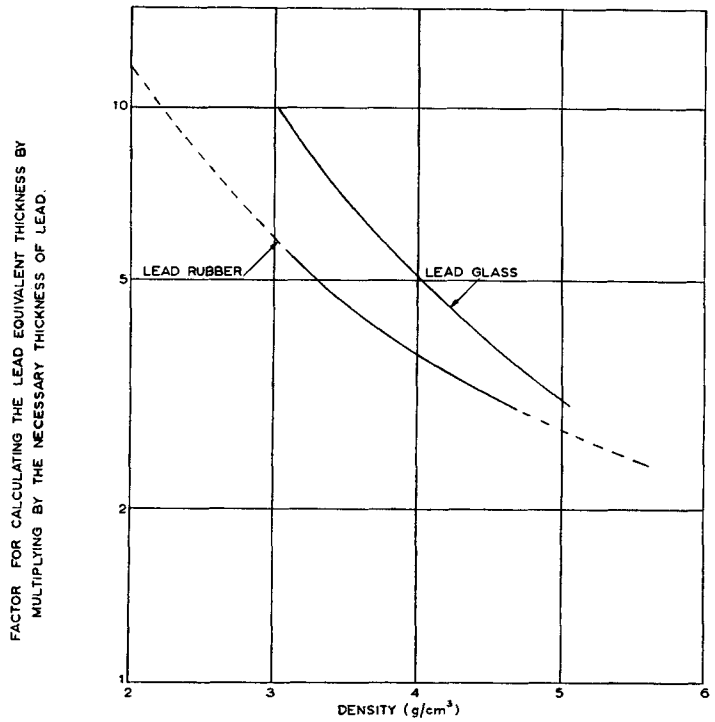

FIG. D6.

Lead equivalents of lead-glass and lead-rubber as a function of density.

to be measured is of sufficient size so that it completely surrounds the counter or chamber. This condition must, however, first be determined with the fluorescent screen.

(b) Quantitative measurement of doses (or dose-rates)

The exact measurement of dose or continuous dose-rate at occupied positions shall be carried out with the X-ray tube operating at the maximum voltage and dose-rate.

In general, measurements should also be extended to all occupied rooms or places in the near surroundings (above, below and adjacent).

Only ionization chambers, Geiger-Müller counters, scintillation counters, etc., whose response is reasonably independent of the quality of the radiation, and whose sensitivity can be checked by means of, for example, a radioactive control, should be used.

Dose-rate meters should only be used when the operating conditions remain unchanged over long periods of time, as, for example, for therapy installations, fluoroscopy and some industrial radiography.

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[1] Care should be taken if pulsating radiation is to be measured.

In the case of variable dose-rates and short X-ray exposures (radiographs), dose-rate meters are unsuitable for other than rough estimates. In such cases, integrating dose-meters with which the dose per radiograph or per series of photographs is found, should be used.

(*c*) *Report on a radiation survey*

Some proposals are given below regarding items which might be included in the report of a radiation survey.

Often it is advisable to provide an isodose diagram for the course of the limiting value of 6 mr/h, if exposure times should reach 48 hours/week. When, as mentioned above, the irradiation time is limited to less than 48 hours/week, higher limiting values may be permitted. In all cases of this kind, the time during which one can remain without danger should be posted at all occupied places.

If practical, a scale diagram should be added in which the X-ray machine is shown and the positions of personnel are marked by numbers or letters. Dose-rates for these positions can be given in a table. In the diagram the positions of personnel located in the region of possible radiation danger should be particularly distinctly brought out and it should be pointed out when and where protective aprons and protective gloves should be worn.

The report should contain brief recommendations for improvements in techniques, protective wall thicknesses and limitations of the beam or running time, by which radiation hazard is removed or reduced. The emphasis should always be on improving protection wherever necessary in order that no limitation in running time is imposed. The report should also state whether, after removal of the radiation hazard, a further check is required.

9. *Approximate dose-rates in diagnostic examinations*

(*a*) *Radiography*

In Table D.X are given the average values of doses in r with "normal operating conditions" and with modern, highly sensitive radiographic and photographic material. Earlier measurements by Lemmel or Martin give higher dose values because of less sensitive films and intensifying screens.

TABLE D.X

AVERAGE SURFACE DOSE PER EXPOSURE (FRONT FIELD)

Organ	Tube-potential (kV)	Dose in r
Fingers and hands (without screen)	40–50	0·06
Shoulder	55–65	0·7–1·0
Skull lateral	60–65	0·8–1·2
Skull in front	65–75	1·2–1·6
Spine lateral	70–85	1·8–3·5
Spine in front	65–75	1·6–2·5
Pelvis	70–75	2–2·5
Lungs (distant)	60–75	0·04–0·2
Stomach	75–90	1·5–3
Bile	75–90	1·5–1·9
Kidneys	65–85	1·4–2·5
Teeth (near) (without screen)	50–60	3–5
Forehead (frontal sinus) contact-radiography	65–70	up to 75
Lungs, tomography with transversal layer	75–80	0·5
Heart (kymography)	85–90	2–4
Lungs (mass-miniature radiography)	75–80	0·2–0·5
Pregnancy	85–95	3–6

(b) Fluoroscopy

TABLE D.XI

AVERAGE SURFACE DOSE-RATE (FRONT FIELD) WITH "NORMAL OPERATING CONDITIONS"

Target-skin distance 35 cm, tube current 3 mA.
(Lemmel, Martin, Sorrentino and Yalow, Wachsmann, Mayer and Zakovsky.)

Tube-potential (kV pulsating)*	Average dose-rate (r/min) for small and large fields with the following total filtrations (in mm Al equivalent)		
	1·5 mm Al	2 mm Al	3 mm Al
60	7 r/min	4·5 r/min	3 r/min
80	14	10	6
100	20	15	10

* It should be observed that in larger X-ray equipment, cable capacity makes the voltage relatively constant and the measured dose-rates may be higher.

(c) General considerations

Increasing the filtration to thicknesses above 1 mm Al equivalent enables a considerable reduction to be made in the dose to the patient (see Fig. D7).

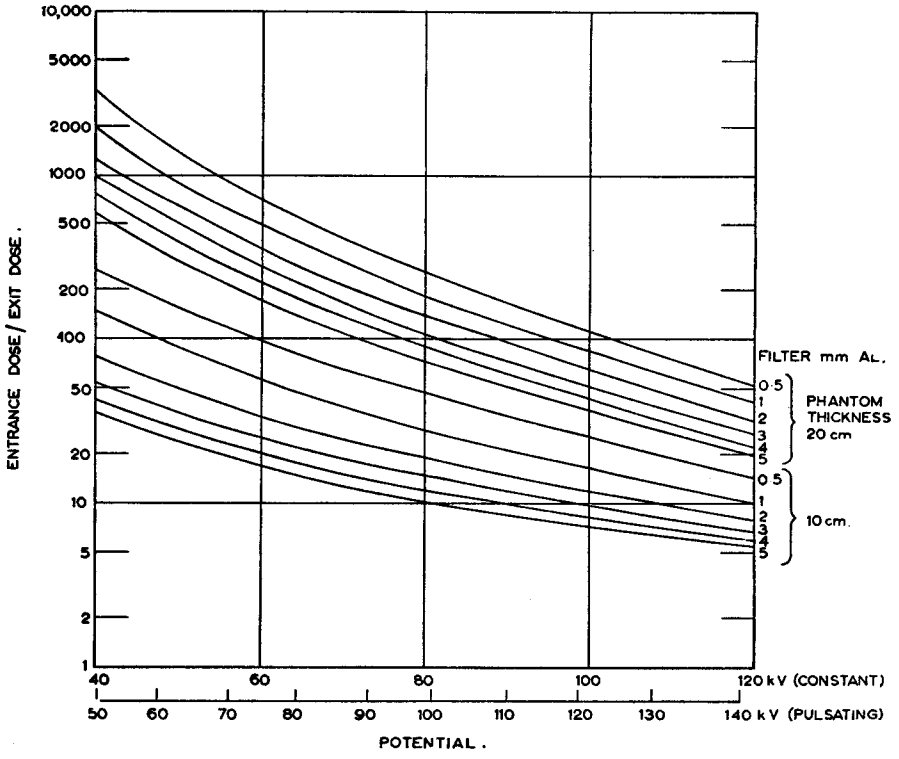

FIG. D7.

Dependence of the ratio entrance dose/exit dose upon filtration (in mm aluminium) for various tube potentials and phantoms of 10 and 20 cm thickness, without scattered-radiation diaphragms.
(Wachsmann, 1951.)

In order to reduce both the skin dose to the patient and the dose of scattered radiation reaching the operator, the following recommendations are given:

(i) fast film should be used;

(ii) higher potentials may frequently be used without detriment to the diagnostic quality of the film; and

(iii) added filtration of the primary beam up to 3 mm Al should almost invariably be used. (See G. M. Ardran and H. E. Crooks, 1953.)

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E. REPORT OF INTERNATIONAL SUB-COMMITTEE IV ON PROTECTION AGAINST X RAYS ABOVE TWO MILLION VOLTS AND AGAINST BETA AND GAMMA RAYS, AND OF INTERNATIONAL SUB-COMMITTEE V ON PROTECTION AGAINST HEAVY PARTICLES, INCLUDING NEUTRONS AND PROTONS

I. INTRODUCTION

Although, when it was set up, Sub-Committee IV was asked to deal with X rays excited at potentials above 2 MV, it was later realised that, in view of the recommendations of the I.C.R.U. that the röntgen is still applicable for X and γ rays up to quantum energies of 3 MeV, it would be better if the figure of 3 MeV rather than of 2 MeV were taken as the starting point of the recommendations of Sub-Committee IV.

II. PERMISSIBLE DOSE FOR EXTERNAL X AND GAMMA RAYS OF QUANTUM ENERGIES ABOVE 3 MEV

For quantum energies above 3 MeV, the dose should be expressed in terms of the rad, the permissible level being 300 mrad per week in any part of the body.

III. PERMISSIBLE DOSE FOR EXTERNAL NEUTRONS

The permissible exposure to neutrons in the energy range 0·025 eV (thermal) to 10 MeV shall be either:

1. that exposure which should produce an energy absorption of 30 mrad per week at a depth of 2 cm below the surface of the tissue, or

TABLE E.I

NEUTRON FLUXES

Neutron energy	Neutron flux n/cm²/sec
0·025 eV	2000
10 eV	2000
10 keV	1000
0·1 MeV	200
0·5 MeV	80
1 MeV	60
2 MeV	40
3–10 MeV	30
In these calculated values, it is assumed that the R.B.E. for γ rays is 1, for protons is 10, and for heavy recoil nuclei is 20, in accordance with Table E.II	

2. exposure for periods not exceeding 40 hours per week, to the neutron fluxes given in Table E.I

IV. R.B.E. VALUES

It is convenient, in practice, to relate R.B.E. to the type of radiation and the biological effect. The following R.B.E. values are recommended. (See also report of Sub-Committee I.)

TABLE E.II

R.B.E. VALUES

Radiation	R.B.E.	Biological effect
X rays, γ rays and electrons and β rays of all energies	1·0	Whole-body irradiation (blood-forming organs critical)
Fast neutrons and protons up to 10 MeV	10	Whole-body irradiation (cataract-formation critical)
Naturally occurring α-particles	Compare with 0·1 μc Ra, otherwise = 10	Carcinogenesis
Heavy recoil nuclei	20	Cataract formation

V. UNIT FOR EXPRESSING RADIATION INTENSITIES FOR HIGH-ENERGY RADIATION

The International Commission on Radiological Units defines "intensity of radiation" as "the energy flowing per unit time through unit area perpendicular to the beam. It is expressed in ergs per square centimetre per second or watts per square centimetre" (1953). The Sub-Committee recommends that, for high-energy radiation, radiation intensity shall be expressed in terms of watts per square centimetre.

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